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A GUIDE TO PUBLIC DATA RESOURCES FOR A CIRCULAR ECONOMY MODELLING AND MEASUREMENT FRAMEWORK

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A guide to public data resources for a circular economy modelling & measurement framework

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Report outline

The UKRI National Interdisciplinary Circular Economy Research (NICER) programme is a £30 million, four year programme made up of five research centres each focussed on a resource flow of strategic importance to the UK economy. The objective of the NICER programme as a whole is to move the UK towards a more circular economy, including through demonstrating the economic, social and environmental potential of applying whole-system circular economy (CE) interventions at a variety of scales to those five strategic resource flows of focus and beyond. At the centre of the programme is the CE-Hub, the role of which is to coordinate evidence development across the five centres with regards to the value creation potential and costs, enablers and barriers, wider impacts and risks associated with different configurations and levels of circularity.

Therefore, a focus of the observatory has been to establish an agnostic approach to consistently and comprehensively assess the desirability of different circular economy configurations and define and track routes to realise these. The analytical steps which comprise the observatory approach to measure (and appraise) the value creation (potential) and wider impacts of greater circularity, carry data input requirements ranging from hierarchical lists detailing the material make-up of products, to time series data on the flows of products through the economy and value-added across value-chain steps. The methodologies underpinning the analytical approach are widely employed to help answer stakeholder questions relating to the circular economy. Observed secondary data is generally given priority for meeting input needs.

This working paper identifies and curates publicly accessible data[1] identified as relevant to populating the observatory analytical framework input requirements and broad statistical basis for indicators to monitor, steer and appraise improvements in circularity and its impacts. A qualitative 'gap assessment' of the coverage of data in relation to these input requirements is provided. In addition, limitations in (meta)data assets and data infrastructure encountered in the process of finding, accessing and potentially integrating sources are highlighted (Wilkinson *et al.* 2016). Considering these, the paper goes on to set out steps which are being taken by the CE-Hub in the near-term to operationalise the framework and apply it across a range of cases. It lastly makes several recommendations on steps which can be taken by data producers, publishers in particular, to address identified issues going forward and to potentially wider benefit in developing the evidence base for a more circular, environmentally sustainable and prosperous UK and beyond.

[1] Understood in this context as data sources made available for access by members of the public and which are usually, but not always, those provided by public sector actors

Executive summary

Aim of paper

As part of its work coordinating evidence development across the UKRI NICER programme, the CE-Hub has:

1) Sought to identify key stakeholder questions and data needs to guide the focus of a CE data observatory;
2) Established a taxonomy of key terms and concepts to describe CE-related flows, interventions and dynamics at different scales;
3) Reviewed analytical methods and key performance indicators (KPIs) for measuring and monitoring outcomes and impacts across sectors within a consistent analytical framework; and
4) Assessed gaps in data sources to quantify those KPIs and apply relevant methods.

This working paper advances on fulfilling objective 4. It does so by identifying publicly accessible data relevant to input requirements of the modular and agnostic analytical framework developed by the CE-Hub to test the impacts and opportunities of different circular economy configurations and map and track pathways to realise these. To date, the analytical framework has been applied across a range of cases as part of the NICER programme to help illustrate the value-creation potential of the more circular treatment of goods and services based on a 'whole systems' approach. The analytical methods underpinning the assessment framework are widely used in the appraisal of circular economy options furthermore, making our assessment relevant to stakeholders in this area of study.

The paper curates shortlisted data assets in terms of what they are able to tell us and how they contribute to painting a picture of the UK circular economy. In doing so, it provides a high-level[2] gap assessment of the current coverage of UK public digital data in relation to input requirements of the developed analytical framework. The paper goes on to examine shortlisted data assets, their associated metadata and relevant data infrastructure (used for discovering and retrieving those assets) against dimensions of fitness centred primarily around the FAIR principles (Wilkinson *et al.* 2016) and extended to aspects of further relevance such as timeliness.

Whilst recognising a significant amount of data are published by non-UK actors (including supranational bodies) and private organisations (including on a commercial basis), the focus of this particular working paper is primarily on data published by UK public-sector organisations. In cases of particular data gaps or where non-UK sources might need to be drawn on e.g. in multiregional input-output databases, we do describe additional relevant sources if found through the search methodology. Further assessment of additional commercial data sources and those made available publicly by non-public sector actors would be valuable.

[2] It is recognised that data coverage may vary significantly across different resource flows. It is also acknowledged that many relevant sources are likely to have been missed here and we welcome feedback regarding these.

Key findings

Coverage

In relation to the data input requirements of the multi-level analytical framework developed by the CE-Hub to assess circular economy transitions, our search identified at least 112 digital data assets of potential relevance. Our initial findings suggest that current data coverage is varied across and within the layers of input requirements (outlined in section 1) and several gaps appear to exist. Some of these gaps were found to be consistent across value chains and scales, such as our understanding of secondary materials entering into different products, industries and the country as a whole. Identified data also varied in their detail and timeliness, reflecting the variety of different purposes for which they are collected and published. We outline key findings in relation to each layer of the framework below.

Material, component and product-layer

To trace materials, components and products across the UK along with their physical impacts, key data inputs include on: physical flows and stocks (or lifespans as a basis to estimate missing values); the material composition of products and components; and impact characterisation information. Our review found that:

- A large number of the data sources identified provided information relevant to tracing flows and stocks, with some covering raw materials up to finished products and others focussing on a subset of these. Some sources covered multiple material/product groups and others were group-specific.
- Available data were found to be concentrated in some areas of the value chain and relatively scarce in others. Data were reasonably complete for inflows (e.g. imports and consumption) and outflows (through regulated waste systems and exports). Gaps were evident for many material/product groups across reverse loops particularly outside of recycling such as resale, refurbishment and remanufacturing. Gaps were also evident at the use phase outside of the product-groups of vehicles, buildings and electronics. Data on lifespans were identified for some products but often from one-off studies or irregularly updated. Data were more complete for some institutional sectors e.g. households, than others.
- In many cases, published data are at a level of aggregation which makes it difficult to get insight into flows and/or stocks of individual products or materials, including those of strategic importance. For instance, flows of rare earths into various end-use applications across the economy cannot easily be discerned from current published data (Lusty *et al.* 2021).
- No data asset was found to capture information for any material, component or product across all value chain stages from its entry into the UK economic sphere and out. This means and where these are available, several sources need to be drawn upon to provide a value-chain-wide picture.
    - Some frictions to link data in this way include varying levels of detail and differences in identifiers, definitions and measurement boundaries which make it difficult to know if the same thing is being referred to across sources. Whilst statistical and data science techniques can enable many of these issues to be overcome, the result of varying work-arounds taken by different users can be inconsistencies and a lack of comparability in analytical outputs.
- Outside of specific areas such as food, textiles, household chemicals and cosmetics or where hazardous substances are involved, there appear to be limited requirements for information on a

product's material makeup to be made publicly available in the UK and even where so, this is rarely collated digitally.
    - Therefore, compositional data (which can help move between product and material-levels of assessment) including in a bill of materials (BoM) format, were found to be limited in availability and otherwise fragmented across sources. What was available was restricted to only some product groups with poor up-to-date coverage of the range of products falling within these and generally archetypal rather than at a brand or model-level. This gap in compositional data has been identified in other studies e.g. Løvik *et al.* (2021).
- Completed life-cycle assessments and particularly those publicly accessible, were few relative to the total number of products entering the UK market. Estimating baseline and against-baseline lifecycle impacts as part of bespoke assessments therefore requires the use of impact characterisation factors in most cases. These are available to varying degrees, with gaps in factors relating to the impacts of new technologies relevant to the circular economy.
    - The robustness of these inputs requires further examination but have been noted elsewhere to be undermined by inconsistencies in accounting approaches (Wiedmann *et al.* 2006) and limited in their communication of uncertainty (Moni *et al.* 2019) notwithstanding drives towards greater standardisation. Furthermore, there was limited coherence between categories of impacts for which data is usually collected at the micro-level, versus those at meso and macro-scales (Steubing *et al.* 2022).

Distribution of sources identified on product flows and stocks across value-chain stages[3]

	Inflow	Use	Outflow and reverse flows
Construction	6	2	8
Vehicles	4	1	7
Electric vehicles	1	1	0
REE-Ms	0	0	0
Electronics	4	1	8
Packaging	4	0	8
Textiles	3	1	7
Food	2	0	6
Furniture	3	0	3

Activity layer

To test the financial feasibility and wider economic implications of changes in value chains towards greater circularity, methods drawn on as part of the analytical framework include stakeholder mapping, life cycle costing and financial and social cost-benefit analysis. These have information requirements

[3] These sources may not be specific to, or comprehensive of, each of these product groups and value chain steps listed, but rather capture information *relevant* to them. That sources have been identified as relevant to an input does not necessarily mean that there is full and coherent coverage of the information required.

broadly including but not limited to: entity registers; financial performance data; and information on market prices and externalities. In relation to these data input requirements, our search found:

- Several sources (5) which could help identify relevant entities across value-chains. This included partially digitised Companies House data covering UK businesses, HMRC's trade statistics for domestic entities engaged in international and UK cross-border trade and Environment Agency (EA) registers used in monitoring and enforcing a range of central government regulations. Much of this came with detailed locational data (though with possible issues around reliability) and identifiers which could help make linkages with other sources e.g. by Standard Industrial Classification (SIC).
- For constructing a picture of domestic value chain transactions in financial terms and the number of domestic logistic steps and profit margins that business model changes towards greater circularity may reconfigure, identified data showing relationships between entities were available only on a fairly aggregated (e.g. ~100 industry) basis. Data sources capturing information on firms by market share were not captured in our review but could otherwise help develop a picture here.
- For extra-domestic value chain transactions, data on trade in goods was provided at a detailed level in monetary terms via HMRC's UK Trade Info site, which adopts a passive suppression approach in releases. This only captures information for flows directly crossing the UK border and between UK countries however, and not transactions further upstream. Global MRIOs primarily maintained outside of the UK provide information-here, but too at a quite aggregated level.
- To help characterise a baseline across value chain actors, some data on firm-level financial performance were found to be retrievable from digitised publicly accessible Company Accounts, with reporting requirements varying by business size but broadly including variables from profit and loss accounts and balance sheets such as income, expenditures, profit, assets and liabilities. Additional public sources collecting data on parameters such as sales or gross value added were found to be published at a more aggregated level, though with active suppression for confidentiality purposes leading to many areas of information being publicly unavailable.
- Financial data on expenditures by units in institutional sectors outside of corporations e.g. government bodies or households were too identified, ranging between that particularly detailed (as for households) to those more aggregated (e.g. local government costs around waste management). Altogether, these sources constitute a fairly rich basis of financial data, including to support distributional analysis in some cases.
- To analyse and compare more circular configurations against-baseline, required investments and potential changes in extra-OPEX financial variables need to be estimated. For this, a range of unit price inputs were identified, including for components of consumer-price indices, labour inputs, relevant services (e.g. for waste management) and taxes. These can also be derived from data on the sales of manufactured and traded goods.
- Publicly accessible information on prices for aspects closely linked to the circular economy such as secondary-materials were relatively scarce however, as were those on capital expenditures- though further exploration of available public lifecycle costing databases is needed. Given the frequently very specific information requirements for financial cost-benefit analysis, it is difficult to generalise regarding coverage here.
- Extending a financial cost-benefit analysis to consider social costs and benefits requires data on externalities where present (i.e. wider economic impacts not internalised in market prices). Our search identified a limited number of data sources made available on a public basis capturing information on the value of externalities, including in relation to the breadth of life-cycle impact categories. This is to be expected to some extent given the high information requirements to generate these. The most readily usable were published by the UK Government as part of its

supplementary guidance to the Green Book and concentrated in areas such as atmospheric emissions, noise and health impacts.
- Some historical studies capturing disamenity effects of waste treatment options were also identified, as were sources supporting natural capital impact valuation. These would require further steps to 'transfer' values to an assessment.

Input requirement	***Sources identified (number)***
Entity registers	5
Prices	9
Firm baseline financial data	7
Externality data	2

Meso-level

The next layer of the observatory analytical framework involves appraising and tracking change and impacts at the 'meso'[4] level. To extrapolate value creation and other indicators modelled at a firm or value-chain scale to that of sectors requires the use of credible scaling-factors. Further accounting for secondary inter-industry and inter-institutional effects requires information such as on multipliers. To monitor meso-level change *ex post*, data inputs are required on material and monetary flows across industries comprising linear and circular economy activities along with their impacts. From our review of publicly accessible data capturing information relevant to the meso-level, a variable picture of availability in relation to these input requirements was found, specifically:

- Sources capturing data in monetary/economic terms were well represented at the meso-level. These help describe the economy across a range of parameters including the value of production, income, expenditure and capital assets across meso-level institutional sectors.
- Identified sources can go some way to helping scale preceding micro-level assessments in order to simulate potential wider implications of business-model and consumption changes along with secondary effects.
- When looking at activities across both linear and circular value chains, established industry classifications which underpin the collection and collation of meso-level economic data in the UK (and increasingly, that environmental) do not demarcate activities associated with the circular economy such as remanufacturing and biorefining, rendered these effectively invisible in public economic statistics at present. This has knock-on effects, furthermore, for estimates of the size and economic contribution of activities making up the circular economy at the national-level.
- Responsiveness to changes associated with a circular economy of some economic variables in the UK National Accounts may also be limited due to their measurement boundaries and construction. For instance, national balance sheet estimates for non-financial capital stocks are based on fairly irregularly updated lifespan assumptions, meaning a lag in any changes in the published value of capital stocks is likely to be seen even if asset residence time were to increase.

[4] Meso broadly refers to any grouping of institutional units between micro and national levels.

- From the reviewed sources, our current understanding of material flows at the meso-level such as for industries, is quite limited. While consumption-based statistics offer insight into global primary used raw material extraction driven by components of final domestic demand and including gross fixed capital formation, data gaps exist regarding apparent and upstream material inputs into producing units e.g. by SIC. In addition, our understanding of material flows between producing units at a meso-level from currently available data remains limited. Available sources such as Prodcom and trade statistics as well as data in specific production areas e.g. agriculture or construction, could be collated further as a means by which to fill these gaps.
- Waste generation and waste treatment data varies in its coverage, robustness and detail across value-chain institutional sectors, being relatively well detailed for households and local authorities, but less-so for producing units such as within the commercial and industrial or construction sectors. Estimates of waste generation by high-level sector were identified, as were those by broad NACE category though published biennially, with a high lag and the calculation approach for which was uncertain. Key data sources on waste treatment omit the source from which transfers are made at present, something Defra's waste tracking system may go some way to resolving.
- A range of impact-related data published at the level of industries and sectors was identified through our search, including for atmospheric emissions and point- and nonpoint source releases to water and land. One issue identified with these sources is that they consider only direct impacts e.g. of greenhouse gas emissions, but not those impacts potentially *avoided* such as waste management's possible emissions savings through offsetting virgin material production. Difficulties here include a high degree of uncertainty in effects and the need to engage in changing wider international accounting norms.
- A breadth of data capturing changes in the state of the natural environment were also identified, however sources linking these to pressures generated by institutional units were not, leading to a degree of disconnect in our understanding of cause and effect. Resurgent interest in the development of macroeconomic output measures e.g. GVA adjusted for externalities as part of SEEA framework guidance, may see further implementation to support this going forward.

Input requirement	***Sources identified (number)***
Extrapolation factors	3
Additional industry/sector level economic data	12
Industry/sector level material flow data	3
Industry/sector level environmental impact data	8

National-level

By building on outputs of assessment undertaken at all prior layers of the CE-Hub framework, the full range of input requirements outlined in this document are relevant to *ex ante* assessment at the national-level. Against-baseline appraisal of the overall potential outcomes and impacts for the economy, society and environment/environmental pressures of more circular configurations net of secondary round effects and alongside retrospective tracking of national performance along those same lines, requires data inputs including: supply and use tables, environmental accounts and wider impact data. Based on the review undertaken:

- As at the meso-level, there is a reasonably comprehensive coverage of variables describing the linear economy in monetary terms and including in relation to economic dimensions such as jobs. Nevertheless, identified gaps in classifications impacting relevant detail in meso-level figures for circular economy activities also propagate through to the national-level. This undermines our ability to paint an overall picture of the size and economic contributions of more circular activities in the UK.
- Compared to the meso-level, there is a more complete picture for many dimensions of material flows at the national level, though remains a mixed picture. This includes primary material inflows in apparent and raw material equivalent terms (i.e. the global material footprint of the economy), though gaps around total secondary material inflows outside of specific material groups such as aggregates exist. In addition, the granularity of insights into flows across more detailed value-chain steps is fairly limited, with gaps such as for total material inputs into total domestic manufacturing, inventories or physical stocks in the use phase.
- At the outflow stage, statistics on total national waste generation were identified as being published on a biennial basis, including with a breakdown of waste treated by various routes. These do not capture all reverse loops such as remanufacturing or resale, however.
- Since the UK's EU Exit, headline estimates for national circularity are no longer maintained at a UK-level as was the case with the 'Circular Material Use Rate' metric calculated by Eurostat. It is understood there is work currently underway by the NGO Circle Economy to produce an updated figure estimating national circularity based on a ratio of material recycled in relation to raw material consumption. No figures for the total domestic material stock were identified at this time.
- A breadth of impact-related data at the national level were identified. For environmental dimensions, these included for emissions and other pollution releases as well as the state of the natural environment. For economic and social dimensions these included data on jobs and surveys of perceptions such as of local cleanliness. Data on the state of, and benefits from, natural capital were also identified alongside that tracking other capital stocks e.g. those built, human and social in various terms.
    - Together, these can allow for tracking the state of the UK across a breadth of variables. Due to the limited granularity in many of these e.g. by geography, it would likely remain difficult to attribute change in some categories to circular-economy outcomes ex post. This difficulty can also arise as a result of the unit in which data is presented e.g. natural capital assets only being tracked in monetary terms at present.

Fitness

Data, metadata and data infrastructure reflecting the 'FAIR principles'[5] can help reduce barriers to incorporating information into analytical workflows and deriving value from it. From our assessment of the fitness of shortlisted data assets and their associated metadata against the FAIR principles using the semi-automated FAIR Evaluation Services Tool (Wilkinson *et al.* 2019) extended to aspects around methodological transparency and timeliness, several broad messages emerged.

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[5] The FAIR principles are a set of development principles for producers, publishers and managers of data assets designed to improve their usability (with an emphasis on machine usability) and, in turn, their value-added (Wilkinson *et al*. 2016)

Quality dimension	Issues
Findability: To make use of data, it first needs to be found. According to the FAIR principles, the findability of a data asset is largely a function of: its identifier scheme; informative (and machine-readable) metadata; and effective registration and indexing of (meta)data assets within established search infrastructure.	Data assets identified as relevant can be found with varying degrees of ease. While asset identifying schemes such as DOI support digital content persistence more reliably than URLs, in no cases (**0%**) was the identifier for a data asset or its associated metadata tested to be likely persistent. Half (**52%**) of assessed digital assets were found to have their metadata contain the unique identifier of associated data, while in no case (**0%**), were returned metadata found to contain an identifier to the metadata entry itself. More generally, metadata completeness was found to vary. Fairly high levels of domain-specific knowledge was required to find some sources, with not all indexed in established search infrastructure or directly retrievable using relevant terms. The overall implication of issues around findability was that the discovery of relevant sources can take a significant amount of time, requires high levels of manual searching and it is likely that many sources of value and enclosed variables have been missed altogether.
Accessibility: Once a relevant (meta)data asset has been discovered, the next step in potentially making use of it is to determine whether it can be accessed. While there has been a concerted drive towards greater accessibility across data published by public sector actors[6], in relation to the FAIR principles specifically, the potential accessibility of (meta)data assets is enhanced through being retrievable by its identifier(s) using a standard communications protocol which is: 1) open, free and can be universally implemented; and 2) allows for authentication and authorisation, where required[7].	**53%** of shortlisted data assets were found to be retrievable using an open protocol for both humans and machines which allowed for authentication and authorization, where required. The equivalent figure for metadata was **100%**. No (**0%**) (meta)data asset was found to have a persistence policy. Most sources reviewed were found to be free to access and planned uses as part of the observatory were expected to meet usage restrictions if there were any[8]. File types were generally open access, with only a small proportion (**12%**) of reviewed sources found to be released in a proprietary data format.
Interoperability: Applying the observatory analytical framework requires the integration of data from a variety of sources. Interoperability broadly refers to the ability of different systems to accurately and unambiguously exchange data (Geospatial Commission, 2022). In accordance with the FAIR principles, interoperability between (meta)data assets can be enhanced by: (meta)data being: machine readable; consistently classified using well-defined metadata schemes and controlled vocabularies; and relevant external information assets (including definitions) being make explicit in	Data was found to not always be provided in a file format (e.g. CSV) or structured in a way that supported automated workflow processing. For instance, terminology and data sheet structures vary between publications. At a semantic level, while sources offer useful information in their own context, the fairly disparate nature of data production has resulted in limited consistency in the use of classifications and definitions when referring to similar things, which can present barriers to comparability and aggregation[9]. Outward references to third-party resources were missing for about three-quarters (**72%**) of reviewed assets.

[6] In line with The Public Sector Bodies (Websites and Mobile Applications) Accessibility Regulations 2018.

[7] The FAIR principles are equally applicable to data made available on an open or closed basis, emphasising instead the clear communication of access conditions. While in some cases, data cannot be made available with the technical and legal characteristics to support open and free use and reuse or would require significant resources to do so, by doing so, it removes barriers to its incorporation into a range of applications.

[8] The review methodology underpinning this paper was geared primarily towards sources released by public sector actors which could be expected to be more openly accessible than all relevant data across the ecosystem

[9] The use of controlled metadata vocabularies is endorsed by ISO 25964 and UK government guidance

metadata (Wilkinson *et al.* 2016; Rezaei *et al.* 2014).	A lack of consistency in how data is recorded and shared was identified by the NAO in 2019 and the 2020 UK Data Strategy as limiting interoperability and the potential for positive externalities from data (DCMS, 2020).
Reusability: The reuse of secondary data is a key part of developing an evidence base across the NICER programme. Reuse can be enhanced by metadata containing a range of relevant attributes determining appropriateness for reuse based on information such as provenance, versions, intended or accepted applications and quality issues. (Meta)data released with a clear and accessible data usage licence can also further support reuse.	Approximately a quarter of assets identified as relevant (**22%**) were found to have their metadata point to a licence. The quality and confidence in data appears to vary, though due to inconsistent or absent communication of issues this is not always easy to determine without anecdotal insights. Communication of uncertainty and methodological issues varied. No source was found to be published alongside code used to produce them so as to enable reproducibility/repeatability. The Government Analysis Function's recently released Reproducible Analytical Pipelines (RAP) strategy provides a guide for data publishers, particularly in the public sector, to improve the auditability, reusability and quality of data.
Timeliness and continuity: The Open Data Principles state that data should be made available as quickly and regularly as needed to generate and preserve value. The availability of historic data and continued publication can provide the information-base needed to support a range of uses, though the costs of doing so can act as a counterbalance.	Two-thirds of sources were found to be published on an annual basis but in some cases were published more frequently (monthly and quarterly). On the other end of the scale, many sources were published on an ad hoc basis. Reviewed sources were found to be published with lag times ranging from 1 month to three years. The continuity of publication varied, with some sources released as regular administrative data and future continuity expected, while for other sources discontinuation either entirely or partially was evident.

What we will do

The UKRI NICER programme's CE-Hub aims to provide a point of convergence, national leadership and coordination to, among other things, improve data for supporting a more circular economy in the UK. To this end, the CE-Hub has and will continue to take several steps in building a data strategy for improving the evidence base. These include:

1. **Continue to coordinate with relevant stakeholders to better understand information and data needs:** Since prior to the inception of the NICER programme, we have engaged with a range of industry and government stakeholders to better understand their roles and responsibilities in the data landscape and capture stakeholder questions and data needs to guide programme foci. We will continue to work closely with these stakeholders and others to ensure evidence development aligns with stakeholder needs.
2. **Continue to develop the underlying taxonomy and design of the observatory modelling and measurement framework:** A lack of commonly accepted definitions impede the development of a high quality statistical base around the circular economy (UNECE, 2020a). At the same time, while a growing number of tools have been developed and studies undertaken to support stakeholder decision-making in relation to increasing material, product and system-level circularity, analytical approaches capturing the multi-level complexity of circular economy transitions in a comprehensive and consistent way have arguably been missing to date (Rietveld *et al*. 2019). Therefore, to consistently answer stakeholder questions, a common overarching system representation including, to begin with, a taxonomy of value chain stages has been developed by the CE-Hub. Encouraging its uptake across the NICER programme and more widely is intended to help: improve consistency in analyses, indicators and datasets; guide, map

and retrieve data; and efficiently visualise and communicate information. The taxonomy has been applied to a range of case examples to date including construction, plastics and steel, results for which are in the process of being published.

3. **Fill data gaps**: To populate the models and sub-models comprising the analytical framework developed, we have sought to extract value from public data within the confines of the search frame. Whilst we are exploring additional data published by e.g. non-UK or private actors and also make recommendations for improving public data in line with stakeholder data needs in the following section 'Recommendations for data holders and publishers', in some cases stakeholder requirements for data may be at a level of detail and timeliness which is not practicable or appropriate to be captured within public statistics on an ongoing basis, in addition to possible issues of data sensitivity and cost. As distinct from private, commercial or public data, there can be instances in which pooling data as a club good can yield net-benefits to those within a given 'club' or localised data ecosystem. On this basis and to support cross-value chain decision making, we are currently working with the Office for National Statistics to apply a 'data trust framework' and data pooling approach to boost the visibility of several strategic materials, components and products beginning with the rare earth magnet value chain (which has a strategic importance across a range of electrification technologies).
4. **Develop critical circular economy public data assets centred around a navigable indicator dashboard:** We will continue to explore additional data sources and incorporate these into a metadata catalogue. We are developing an interactive dashboard to add value to these sources in relation to stakeholder questions and help stakeholders easily visualise baseline data, the potential outcomes and impacts of greater circularity and simulate routes to realise these across a range of scales. A selection of KPIs will act as a bridging element between different parts of the taxonomy and underpin *ex ante* comparison of pathways as well as *ex post* tracking. Where particular gaps have been identified through this review and become further apparent in the process of dashboard development, we will work to fill these through collation and state of the art estimation.

Recommendations for data holders and publishers

Improved data and data practices stand to unlock value across the UK economy (Department for Digital, Culture, Media & Sport, 2020). In addition to the actions we will take as part of the CE-Hub therefore, there are several focussed recommendations for actions which can be taken by data holders and publishers to improve the quality of the data ecosystem for delivering a more circular economy going forward.

Theme		**Recommendation**
Data generation	**Public data classifications**	• Statistical classification systems frequently lag the real economy in their descriptive capacity (Bean, 2016). At present, goods and services of relevance to the circular economy are often insufficiently delimited in established classifications, rendering many of these effectively invisible in published statistics (UNECE, 2021a; de Sa and Korinek, 2021). For instance, the UK SIC system omits codes for remanufacturing and biorefining (Oakdene Hollins, 2021; Wrap, 2021). Such gaps can have significant real-world impacts hindering the development of more circular systems, such as limiting the ability to introduce variable tariffs on new versus remanufactured goods or give tailored industrial support. In addition, if growth in the circular economy is expected to yield significant job creation and economic opportunity, improving its representation in established statistics makes sense.

		○ Therefore, and while recognising the extensive time it can take for new classification systems to be developed, a coordinated effort across relevant bodies to better capture dynamics of relevance to the circular economy in statistical classifications for e.g. products and activities, should be a priority including as part of the forthcoming UK SIC review.[10][11][12][13]
	Public data assets	• At present, an absence of national material flow accounts data at a sub-UK level is leading to a reliance on externally commissioned estimates for relevant figures with possible risks around comparability and continuity of data across the UK. The ONS should explore, in conjunction with devolved administrations and relevant departments, the ongoing generation of material flow accounts at a sub-UK level to overcome this. • Closely linked, where there are gaps in economic inputs to enable national-level material footprint estimates to be made e.g. in input-output tables at relevant scales, progress in resolving these gaps should continue. This will help produce responsive and nationally relevant data assets.
(Meta) data management	**Improvements in (meta)data findability, accessibility and interoperability**	• In line with the FAIR principles, datasets and their associated metadata should be disseminated in a consistent machine-readable format, with persistent identifiers for metadata. • Metadata should be completed as far as possible to support discovery, including in line with existing government metadata standards. • In areas identified as specific to the circular economy, data and metadata should try to make use of a controlled terminology such as offered by the proposed taxonomy to increase findability and interoperability.
Data dissemination	**Reusability and transparency**	• Wherever possible, data should be released with a clear indication of use permissions. This is something data repositories and sites linking to data more broadly e.g. gov.uk can help do more consistently. • Data should be reproducible and updateable where use permissions permit. This can be supported through the publication of raw data wherever possible and more reproducible analytical pipelines i.e. data published with the code that produced it. • Though qualitative, and in some cases quantitative, assessment of uncertainty and possible methodological issues were available across sources, this was not always the case. Where practicable and appropriate, improved quantitative communication of uncertainty such as through the use of intervals and density strips is an area where improvement should be made, echoed here by the Economic Statistics Centre of Excellence. • Linked and where quantitative communication may not be appropriate, a high degree of familiarity with data in a particular area is sometimes required to understand methodological pitfalls or considerations which should be taken in using data. Greater communication and consistency in

[10] In some cases, modern data science techniques such as machine learning are being applied to overcome some issues around limited detail in classifications e.g. ESCOE's 'Industrial Taxonomy using Web Data' project

[11] Established statistical response norms see firms report on behalf of their primary activity in most cases. As a result, changes in the classification system are not a panacea for getting a full insight into the value of CE activities as inter-firm and industry shifts in business models where CE designated activities do not constitute a self-reported majority of firm activity will remain unobserved e.g. reverse logistics activities undertaken by a seller. In the case of the 'Environmental Goods & Services Sector' publication by the ONS which captures financial variables across a range of defined sectors not always elucidated in established statistical publications, the proportion of sectors that certain activities make up is estimated based on returns to an additional survey and this may serve as a model for better teasing out activity making up the UK CE.

[12] More fundamental changes in boundaries of the National Accounts may need to be considered to adequately capture consumer surplus benefits of certain circular economy shifts, but these fall outside of the scope of this review. For instance, the Bean Review (2016) highlights that value creation by unincorporated individuals such as in the sharing economy may not be adequately captured by current statistical collection centred primarily around business surveys.

[13] Important work undertaken by the ONS to establish an approach to measuring the 'sharing economy' as updated in 2017 and 2020 can inform this as well as highlighting relevant value-creation outside of industry.

			that communication of methodological approaches and pitfalls would support understanding of reliability.
	Openness	●	All data collected using public funding are advised to become open access, including in structured, non-proprietary file formats.

Looking forward

As now the most significant geomorphological driving force on the planet (Cooper *et al*. 2018), humans and the materials that they extract, harvest and cultivate, move, transform and consume are a key driver of the gradual, yet continuous, systemic and accelerating degradation of many of our natural capital assets seen around the world today (Dasgupta *et al*. 2020). Assuming current systems of production and consumption remain unchanged, it is estimated that the extraction of materials to meet the anticipated demands of a global population in 2060 of around 10 billion people will rise to more than double current levels (UNEP, 2019; OECD, 2019).

When looking at the UK today, many indicators point to the high degree of linearity in its economy and natural capital loss. In 2019, the mass of materials directly entering the UK economy to meet domestic demand stood at more than 500 million tonnes (ONS, 2022), while when accounting for the full upstream material extraction along international supply chains, this figure for primary raw materials specifically was only slightly short of 1 billion tonnes (ONS, 2022). At the same time and in 2018, over 220 million tonnes of waste were estimated to have been generated in the UK, almost 10% more than in 2010 (Defra, 2022). Of that waste generated, a significant quantity is lost from the economy each year, with roughly a third entering landfills or incineration and an appreciable amount entering the natural environment via fly-tipping and littering (Defra, 2022; EA; 2022).

Finding workable ways of meeting humanity's need for food, energy, housing and other goods and services, while simultaneously maintaining the planet's environmental functions and biodiversity, is one of the greatest challenges of the anthropocene (Vince, 2015). Transformative changes in the way we use resources through absolute decoupling of value creation from resource use, the protection, maintenance and rebuilding of natural capital stocks and a shift to low carbon energy is a key part of this. The 3rd Industrial Revolution associated with the rise of digital technologies and digitalization and the 4th Industrial Revolution applying these to areas such as artificial intelligence, robotics and quantum computing have seen data grow in its centrality to the workings of the UK and global economy. An adequate supply of digital information is increasingly critical to the effective functioning of value chains, markets, innovation and regulation.

A move towards a more circular economy presents data challenges and information needs of its own, with materials in the circular economy having longer and more varied lifetimes and higher specification and purity variability. These needs exist across the economy such as in purchasing and capital allocation decisions and most immediately, as an input into opportunity scanning and setting direction. For this, high quality, reliable, relevant and timely data are sought. Whilst only one part of the puzzle and insufficient to meet all data needs across the economy in this transition, improving the coverage and fitness of public data in the way described in this document can help answer stakeholder questions, inform decision-making and reduce uncertainties in the move towards a more sustainable, prosperous and circular economy in the UK.

1. Data input requirements

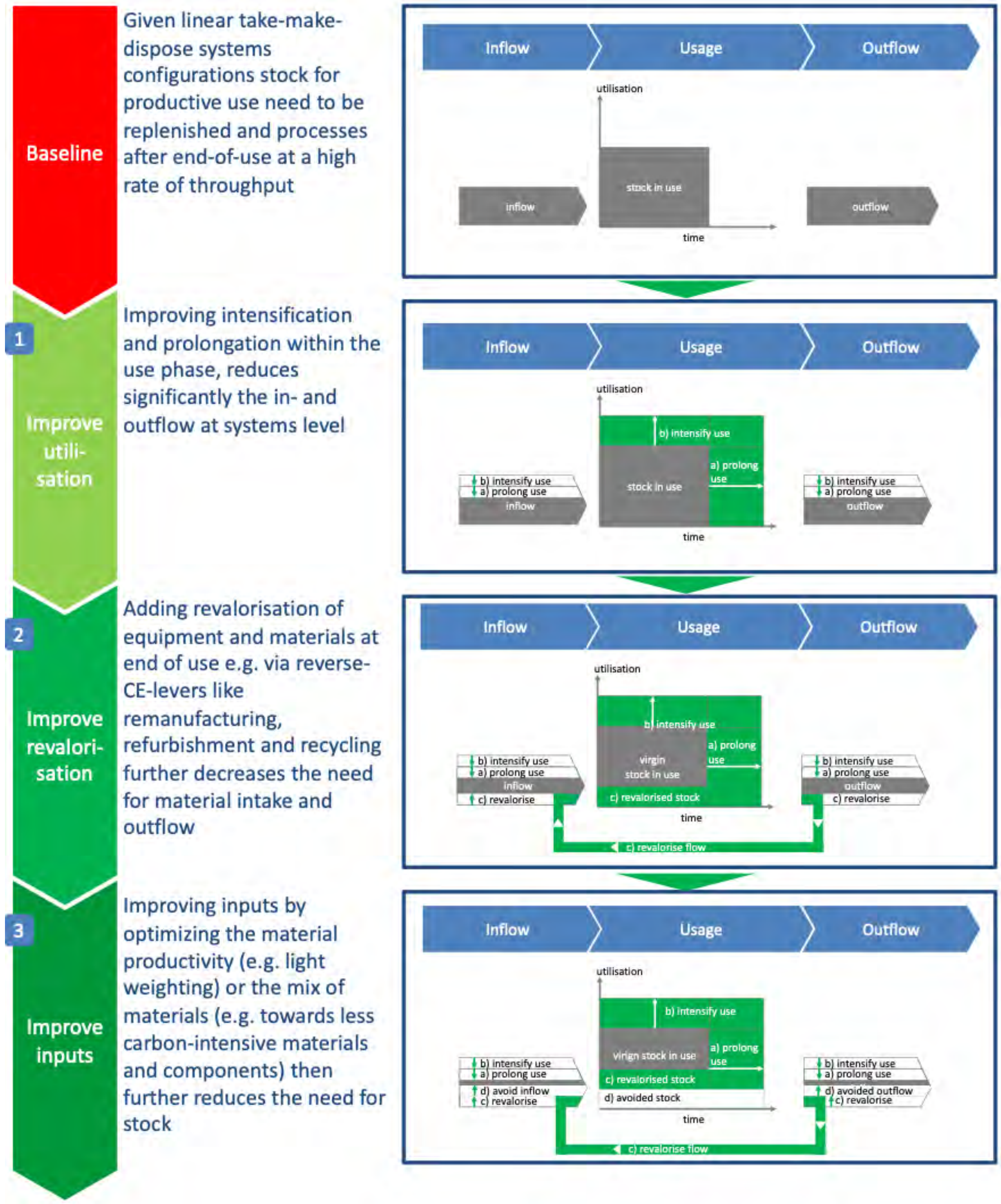
1.1 Analytical framework outline

There are many questions among stakeholders regarding what more circular systems of production and consumption might best look like in the UK, the policies required and costs involved to realise these and possible implications for net zero, natural capital, the economy, jobs and value creation more widely.

To help answer the various questions stakeholders have in relation to transitioning towards more circular business models and systems, a key objective of the UKRI NICER programme's observatory has been to develop a modular and agnostic description, visualisation and assessment framework grounded in a value-chain approach[14]. This is intended to help test, in a consistent and comprehensive way, the value proposition of more circular configurations in resource flows while mapping and tracking pathways to realise these. While the 'circular economy' (CE) is a complex term, some of the key strategies by which CE levers can deliver improvements in resource productivity and carbon benefits are outlined in Figure 1.

Figure 1. Strategies for delivering a more circular economy (Zils, forthcoming)

[14] Value-chain analysis (VCA) involves mapping the steps and activities undertaken by actors along a value chain (VC) which impact flows and stocks of matter, financial value and information from stages of extraction through to point of sale, use and end-of-life treatment.



For any given case of assessment, implementing the assessment framework developed by the CE-Hub broadly involves:

1. characterising a **baseline** or counterfactual current/linear value creation state (including factors contributing to its maintenance which can act as barriers to change), against which to;
2. appraise a portfolio of alternative **future target states** on the basis of consistent criteria and with sufficient incremental detail to help measure and identify trade-offs in outcomes; and
3. determine which **interventions, incentives and indicators** should be used to steer, monitor and evaluate a transformation process between a baseline and sought alternative(s).

Activities driving change in the quantity, quality, location or timing of resource flows and stocks across value chains can have implications for the generation and distribution of financial value between economic entities transacting and holding them, as well as pollution and waste, natural capital stocks, employment, output and society more widely. To capture these diverse outcomes and impacts, a circular transformation for any case is assessed from the 'bottom up' in terms of net or against-baseline change across the following layers:

1. in **material, semi-finished (or component) and finished product stocks and flows**, with implications for impacts associated with these;
2. in **activities** undertaken by actors along value chains such as changes in business models, consumption practices and system-level parameterisation through policy, with implications for economic costs and benefits including externalities;
3. for **value added** in the economy arising at points of transaction and aggregated at the level of industries; and
4. at the **national level** and for the economy, environment and society as a whole while accounting for secondary effects.

Although assessment can be undertaken at any one of the layers in a modular fashion, bridged and nested analysis across them comprise an approach offering a rich, internally coherent and multiscalar structure encompassing all stages of a given value chain and the wider system in which it is situated along with standardised entry-points for measurement and evaluation. Use of the proposed framework is intended to support, among other things: modelling and monitoring of changes in business, value-chain, industry and sectoral CE transformations; the formulation and evaluation of policy interventions; and tracking NICER programme impacts at a portfolio level.

1.2 Required data inputs

To apply the observatory's analytical framework and help answer stakeholder questions, relevant data inputs need to be identified, prioritised, validated and harmonised or in their absence, estimated. Secondary (observed and the, estimated) data are generally prioritised for use, helping focus the observatory's resources on meta-analysis to answer stakeholder's cross-cutting questions while increasing the potential for continuity of monitoring beyond the life of the NICER programme. Sources able to meet multiple data input requirements by providing a high level of detail while covering a breadth of value chain steps are further prioritised.

Modelling inputs

Assessment at each of the layers making up the framework involves the use of methods drawing from a range of analytical disciplines which, in turn, carry information and basic data-input requirements. In Table 1, we outline associated methods and data input requirements for each layer making up the framework.

Table 1. Data requirements by framework layer[15]

[15] The methods associated with each layer of assessment carry strengths and weaknesses and vary in their appropriateness to answering different questions stakeholders may have. For instance, 'bottom-up' or micro-scale methods employed as part of the first of the framework's layers offer a higher degree of accuracy at a detailed product-level which can help in answering granular questions relating to the makeup of products and their flows, though can lend less well to a broad coverage of change at the scale of the whole economy. Also, standard cost-benefit analysis techniques are most appropriate for informing action in contexts of relatively discrete or marginal (price) changes and can work less well outside of these conditions due to: difficulties in capturing structural variation

Layer	Broad outline of analytical process	Analytical method(s)	Relevant information, data inputs and assumptions
1	Tracing the flow and stocks of resources, including embodied within semi-finished (components) and finished products across value chain stages with environmental impacts quantified	Bill of materials (BoM) aggregation model Material flow analysis Life cycle impact assessment	BoM Component or finished product volume flows (and stocks, where relevant) Lifespan assumptions Life cycle inventory and impact coefficients
2	Mapping value chain actors and characterising inputs required to deliver improvements in circularity to determine financial feasibility of options and define wider social cost-benefits	Entity mapping Value chain analysis Life cycle costing Financial and social cost-benefit analysis (CBA) Systems-dynamic modelling	Entity registers Prices Activity costs Firm-level financial data (particularly,value added) Geospatial data Externality values
3	Extrapolating value creation modelled at a firm or value chain level to that of an industry/sector	Assumption-based extrapolation Input-output modelling	Industry and sector-level economic and environmental data National supply and use (SUTs) and input output tables (IOTs) National environmental accounts/environmental data Multiregional input-output database
4	Modelling macro-level impacts net of secondary round effects (multipliers, spillovers and co-benefits)	Environmentally-extended multi-regional input-output analysis (EE-MRIO) Macroeconometric analysis	

Indicators

CE Key Performance Indicators (KPIs) are metrics capturing dimensions of [potential] change identified as important in moving towards a more circular economy, whether enablers, outcomes or impacts. KPIs

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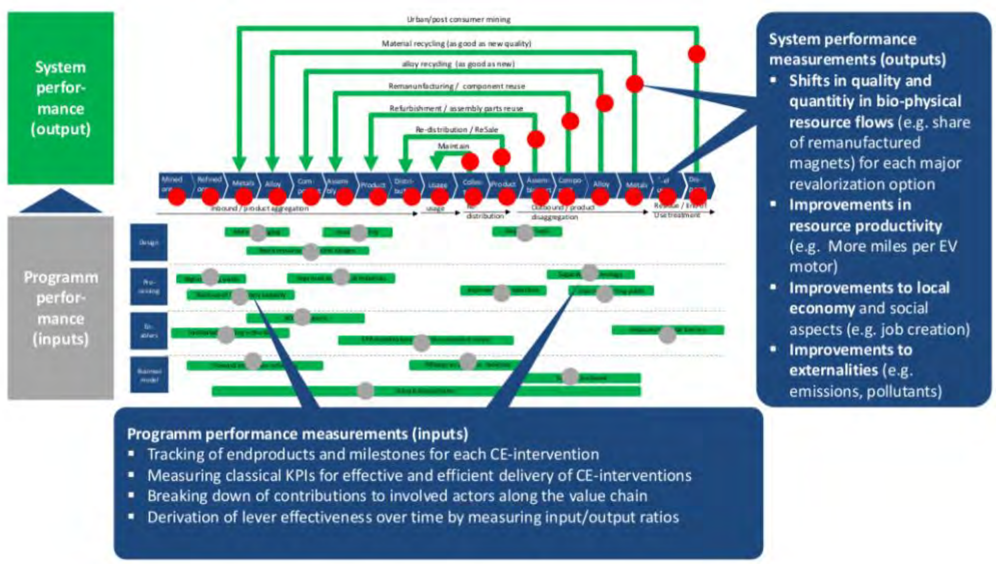
in the economy over time; dynamic effects relating to innovation (Ekins and Zenghelis, 2021); and potential change in the values of macroeconomic variables such as the rate of economic growth or productivity effects (Sharpe *et al*. 2021). Conversely, 'top-down' approaches lending more to meso- and macro-level assessments offer greater comprehensiveness through an economy-wide assessment with potentially better representation of systems dynamics, but provide more aggregated insights (including by extension of the limited granularity of their underpinning inputs) which can distort conclusions at the individual product- or firm-level (Wiedmann et al. 2006; Schoer et al. 2013; Sharp et al. 2021). Coherence across these methods is not always evident furthermore (Steubing *et al*. 2022), though various forms of methodologically integrated hybrid approaches combining, for instance, life-cycle assessment coefficients with EEIO methodologies have been proposed and applied (Wiedmann *et al.* 2006; Schaffartzik *et al.* 2014; Tennison *et al*. 2021).

help track performance (including in relation to objectives) and barriers, support learning around ‘what works’ through evaluation and provide a common unit based on which to assess the desirability of different future configurations. A set of ‘output’ and ‘input’-oriented agnostic KPIs are used across the layers making up the framework to capture performance (Figure 2).

Figure 2. KPI-based monitoring of outputs and inputs (Zils, forthcoming)



‘Output’-side KPIs proposed for use in appraising change occurring across value chains and their impacts as well as ex post monitoring, carry linked data input requirements for their calculation. From the overarching taxonomy of KPIs developed by the CE-Hub (Khedmati-Morasae *et al.* forthcoming), such output or system oriented KPIs include:

- **Physical efficiency** - At its most basic, a measure of efficiency tells us about a relationship between an output and an input in terms of scale. Its calculation therefore requires information on quantities of physical inputs (e.g. tonnes of iron ore) in relation to either the quantity of a desired physical output (e.g. tonnes of crude steel or building floor area) or an undesired physical output (e.g. tonnes of waste) (OECD, 2008)[16].
- **Return on capital employed** (ROCE) which can be used to track the economic benefits of more circular value creation at a product or firm-level along a value chain, requires data on earnings before income and tax (EBIT)–which itself is a function of revenues and operating expenses on one hand and capital employed on the other;
- The extent to which CE financial **value-retention potential** is being realised can be measured using data on the value of sales at the point at which materials/products are reincorporated back into the economy (less the costs of preparation for that sale) and alongside either the value of initial expenditure or counterfactual replacement costs. Alternatively, value-retention processes may be tracked in terms of financial variables including sales and expenditures associated with specific activities (Oakdene Hollins, 2022).

[16] Closely-linked measures of service efficiency alternatively track the quantity of material resource inputs in relation to a unit of service or function such as kW/h energy production or km travelled

- The **economic importance** of material resources to the UK economy can be estimated using data on the end-use applications of a material in physical terms in conjunction with the monetary value associated with those end-use applications (Lusty *et al.* 2021).

Continuing to transition to a more circular UK will require interventions throughout the economy, new and joined-up policy initiatives and cross-sectoral and policy collaborations. 'Input' oriented KPIs help track the transformation processes giving rise to outputs. These include altered business models, improved forms of reverse network management and end-of-life treatment (Hopkinson, De Angelis and Zils, 2020). Recognising that drivers and enablers of more circular outcomes and impacts can be highly context-specific, input-side KPIs can categorised into the following 'building blocks', under which relevant indicators can be derived:

1. **Design** - concerned with how products are designed to support the extended residence time, including for their constituent components and materials within the economic system;
2. **Business models** - concerned with the extent to which circular business models are developing and in place to guide firm transitions to greater circularity;
3. **Processing** - mechanical and bio-chemical processes transforming a material or product in support of more circular systems;
4. **Enablers** - policy/legal, technology, economic and social landscape factors supporting circular transformation.

1.3 (Meta)data and infrastructure fitness preferences

Certain characteristics of data assets (including datasets, associated metadata and data infrastructure) can increase the net value of their use and reuse. This can be through: reduced time costs associated with searching for, cleaning and integrating data; being able to publish findings more reproducibility; and inputs having their accuracy or methodological shortfalls conveyed so as to help communicate uncertainty and the trustworthiness of findings.[17]

FAIR +

The FAIR principles are a set of development principles for producers, publishers and managers of data assets designed to improve their usability (with an emphasis on machine usability[18]) and, in turn, their value-added (Wilkinson *et al.* 2016). "FAIRness refers to a maturation process where digital objects are rendered increasingly self-descriptive to [machines]" (Wilkinson *et al.* 2019, p.6). The principles (outlined in Box 1), follow the logic that the first step in using data is to find them, after which a user needs to know how that data can be accessed, before going on to integrate it into an analysis (frequently alongside other sources) and disseminating outputs.

Box 1. The FAIR (meta)data principles (Wilkinson *et al.* 2016)

[17] The importance of particular characteristics can vary by the intended use of asset(s). For instance, interoperability may become more important for a modelling workflow integrating a variety of data inputs compared to an application in monitoring historical performance in a discrete area. Nevertheless, reflecting desirable characteristics uniformly across all assets can improve the overall quality and versatility of the data ecosystem and the potential for more robust outputs and insights.

[18] Machine-usability, as is emphasised in the principles, is especially key when seeking to perform actions such as the automated discovery, ingestion, filtering and prioritisation of (meta)data, among other things.

Findable:
F1. (meta)data are assigned a globally unique and persistent identifier
F2. data are described with rich metadata (defined by R1 below)
F3. metadata clearly and explicitly include the identifier of the data it describes
F4. (meta)data are registered or indexed in a searchable resource

Accessible:
A1. (meta)data are retrievable by their identifier using a standardised communications protocol
A1.1 the protocol is open, free, and universally implementable
A1.2 the protocol allows for an authentication and authorization procedure, where necessary
A2. metadata are accessible, even when the data are no longer available

Interoperable:
I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation
I2. (meta)data use vocabularies that follow FAIR principles
I3. (meta)data include qualified references to other (meta)data

Reusable:
R1. meta(data) are richly described with a plurality of accurate and relevant attributes
R1.1. (meta)data are released with a clear and accessible data usage licence
R1.2. (meta)data are associated with detailed provenance
R1.3. (meta)data meet domain-relevant community standards

In our assessment of data fitness, we have drawn on the FAIR principles while expanding on them in areas of interest such as data openness and methodological transparency to reflect localised priorities. As part of the FAIR principles, **findability** refers to the ease with which a user is able to identify data. Findability is, to a large extent, a function of effective data curation practices such as (meta)data assets being assigned a unique and persistent identifier at the point of publication, being richly described in metadata[19] and searchable and indexed in relevant catalogues or repositories. Once an asset of potential value has been identified, the **accessibility** of that data then relates to the ability of a user to read and make use of it. Data accessibility can be increased by, among other things, (meta)data being retrievable using a standard request protocol allowing for authentication and authorisation procedures as required, and being structured and published in a format enabling automated workflow processing.

Though FAIR principle R1.1 refers to the presence of a clear and accessible data usage licence, this is equally applicable to data made available on an open or closed basis. 'Open' data refers to free data made available with the technical (e.g. non-proprietary formats) and legal characteristics to enable anyone to use, re-use or re-publish it provided that minimal conditions such as the original source being attributed, are met (Open Data Charter, 2015). While it is recognised that not all data collected can be made fully open for reasons ranging from privacy to copyright concerns, openness (including being free to access for anyone and having a licence in place supporting all or the majority of onward uses) can reduce barriers and costs to deriving insights, public goods and innovative products, including as part of an observatory framework (Pollock, 2009 in Kitchin, 2013). It should nevertheless be recognised that making data open can involve costs and there may be conditions under which data being treated as a 'club good' may be equally advantageous[20].

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[19] Good quality metadata (including being available via a programmatic infrastructure interface) can support storing, preservation, the correct interpretation and efficient assessment of data quality (Zuiderwijk, Jeffery and Janssen, 2012).
[20] For critiques of data openness see Kitchin (2013); Bates (2012); and Helbig *et al*. (2012)

Analysis undertaken across the layers of the observatory framework generally requires the use of diverse data. **Interoperability** refers to the ease by which two or more data resources can be accessed and integrated with one another (Wilkinson *et al.* 2016), with low levels of interoperability imposing barriers and time costs to analytical workflows and machine actionability. One distinction can be made between lower-level *syntactic* interoperability associated with the likes of using consistent data formats on one hand, and higher-level *semantic*[21] interoperability associated with the use of consistent terminology, system boundaries and definitions to support precise transmission of information, on the other (Alfieri *et al.* 2021)[22]. (Meta)data interoperability can be enhanced by, among other things, the use of a formal, accessible, FAIR and shared language for knowledge representation which draws on consistent ontologies and providing references to other related (meta)data assets within associated metadata.

Being able to publish findings transparently such that they can be used in other assessments is a key part of building a robust evidence base regarding the circular economy through the work of the NICER programme. In accordance with the FAIR principles, **reusability** can be increased through (meta)data being richly described with relevant and informative attributes (covering, for instance, version information), being released with a clear and accessible data usage licence alongside detailed information on provenance and data and non-data assets (e.g., reproducible analytical pipelines) meeting domain-relevant community standards.

While ideally any source of data will be produced using a statistically robust methodology, this may not always be the case, or possible, even for widely used and trusted statistics.[23] An important element of building trust in research outputs therefore, is communicating associated (potential) inaccuracies[24] including due to uncertainty, bias or methodological shortcomings. This can help inform the level of confidence or reliability which should be assumed in reusing data. As a key part of provenance, uncertainty or any methodological issues at the level of data inputs being communicated, can further help support the aim of the observatory and the wider NICER programme's ability to communicate robustness of findings in a consistent and transparent manner.[25]

Timeliness

Data inputs being current or up-to-date and regularly updated can increase their value in analytical workflows by supporting timely insights, reducing the need to estimate missing data and providing a richer statistical basis for a variety of purposes.[26] Having historical data also provides context and supports comparison over time. Across the analytical methods and KPIs associated with each layer, up-to-date

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[21] Semantic interoperability is associated with the 'data linkages' concept, which examines the ability to join data through determining whether two records (e.g. for activities or products) belong to the same entity or refer to the same thing (Harron *et al*. 2016).

[22] An alternative categorisation is that proposed by the Healthcare Information and Management Systems Society (HIMSS): foundational interoperability relating to the ability for data exchange alone, structural interoperability relating to data exchange syntax and semantic interoperability building on those prior alongside consistent vocabularies to enable correct interpretation (in Open Data MOOC).

[23] For instance, according to the ONS, the accuracy of the key macroeconomic aggregate gross domestic product (GDP) is not quantifiable given the numerous sources on which it is built.

[24] Accuracy can be understood as the property exhibited by data values when reflecting the true state of the world (ISO 8000).

[25] In addition to via any inputs drawn on, error and uncertainty can also enter an observatory assessment at a process level as a result of a particular methodological design, any omissions, measurement issues and optimism biases.

[26] For instance, for specific uses such as time-series or multivariate forecasting, requirements can include having a sufficient number of data points to ensure statistical robustness in modelled outputs.

data released on established publication cycles which are likely to continue to be published going forward, are prioritised for use wherever available so as to enhance continuity of monitoring during and beyond the life of the NICER programme.

In Appendix I, we further set out the methodology underpinning this review, including both the search and asset selection approach and testing protocol for dimensions of fitness.

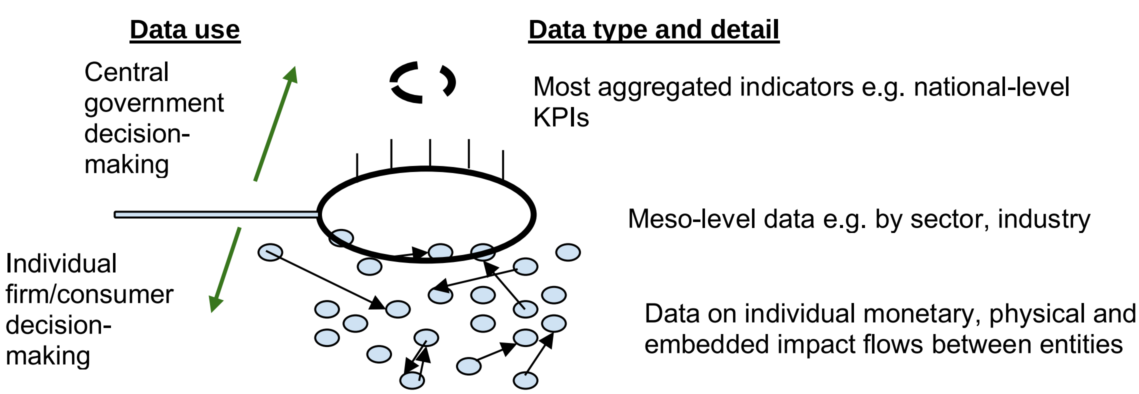
2. Data coverage

In this section, we present data assets identified as of relevance to the observatory framework, outline what they are able to tell, discuss to which extent they meet data input requirements across observatory layers and highlight issues and gaps identified.

2.1 Data producers and uses

UK public sector organisations collect a significant quantity of primary data regarding the UK economy, society and environment today, including via censuses, surveys, administrative data collection, the integration of secondary sources and one-off studies. These can be published as they have been collected, aggregated in some form or transformed to produce secondary outputs. Data collection is driven by a variety of objectives ranging from meeting legal requirements and ensuring compliance to infrastructural planning, resolving information asymmetries, basic research and general statistical collection. In the last two decades and in a context of technological developments and increased interest in the potential for open data to enhance accountability, efficiency and economic outcomes (Cabinet Office, 2012), growing amounts of data collected and produced by public sector actors have been made available online in a digital format via a range of catalogues, repositories, portals and dedicated web pages[27]. Figure 3 presents the types of data which may be collected and produced alongside relevant uses.

Figure 3. Aggregation processes across data uses and types (after OECD 2008)



[27] Along similar timelines, expectations and enablers of extra-financial information disclosure by firms have grown, with data on company- and product-level performance now more widely published in company reports. These are often collected and made more legible by third-party organisations such as technology solutions firms, ratings agencies and NGOs. For instance, a growing number of tools and standards have been developed to support product and firm-level measurement of material flows (including those secondary), including the Ellen McArthur Foundation's 'Circulytics', the Boston Consulting Group's 'Circelligence', WBCSD's 'Circular Transition Indicators' and the GRI 306 Waste Standard. With no mandatory reporting of such data and limited norms for sharing, much of this remains privately held however (PACE, 2020).

2.2 Material, component and product layer

Examples of stakeholder questions relating to layer

1. *Do we have a clear picture or ability to trace product flows entering, leaving and moving through the UK economy, including with a high level of material, temporal and geographical resolution to identify opportunities for revalorisation in a context of growing interest in reshoring and building more resilient supply chains?*
2. *Are we able to tell if products are increasingly being sold as a service?*
3. *Which products might present the greatest potential environmental gains (e.g. embodied emissions) through greater resource efficiency, longer lifespans and more circular treatment at end-of-life?*

Bill of Materials (BoMs)

A BoM is a hierarchical data object providing a (potentially extensive) list of the raw materials, components and instructions required to construct, manufacture, or repair a product. BoMs are generally used by firms to communicate information about a product as it moves along a value chain in order to help navigate regulations, efficiently manage inventory and to support product life-cycle assessments. Utilising component and material shares captured within a BoM data object alongside corresponding information on the volume/mass of flows (and stocks) of products/components, makes it possible to move between material, component and product flows (and stocks) at the micro level.

Outside of specific areas such as food, textiles, household chemicals and cosmetics or where hazardous substances are involved, there appear to be limited requirements for information on a product's material makeup to be made publicly available in the UK such as via labels or registers. Beyond 'McCance and Widdowson's Composition of Foods Integrated Dataset' which captures nutritional content of food, our search did not identify any data source maintained by public actors collating standardised BoM-type information in a digital format. Commissioned studies providing information relevant to this input requirement were also identified, such as that undertaken on energy-using products on behalf of BEIS by the consultancy ICF (BEIS, 2021).

Outside of these and in the academic literature, Babbit *et al.* (2020) provide open-access average BoM data across 11 material groups for 25 common categories of consumer electronic products. These data were collated from studies undertaken over several years and do not appear to be released as part of an ongoing schedule of updates. While useful, the electronics market evolves swiftly such that this information may become out of date with technological change. This has the potential to also undermine the usefulness of the additional source identified from the 'ProSUM' project which tracked and estimated material and component flows for batteries, EEE and vehicles across European countries. Other sources in the academic literature providing insight into product and component composition include Plank *et al.* (2022).

Several private organisations currently offer commercial tools for companies to compile and communicate a product or component's material makeup in a BoM structure, but these were found to generally be retained as private and unpublished as not required in regulation. Furthermore, while product life-cycle assessments (LCAs) usually draw on BoM objects or similar inputs, this component is rarely made explicit in final LCA outputs. An exception to this was found to be the case for some Environmental Product Declarations made for some construction materials, though these rarely capture information relating to circularity. Though there was uncertainty regarding the extent to which it corresponded to a BoM data structure, a final potentially relevant data source is the International Dismantling Information System (IDIS) database. This database collates data submitted on over 200,000 end-of-life-vehicle parts to help environmentally-sound car dismantling and depollution by providing information on vehicle composition and the location of parts, their potential recyclability and safe handling and treatment. Though these data are made available free of charge to commercial end-of-life vehicle treatment operators, public access is not possible at this time.

Table 2. Data assets relevant to the BoM data input requirement

Data asset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown(s)
UK Energy-related Products Policy Study	Material composition of energy-using products and lifespan and economic data.	BEIS	%, mass	UK	Unspecified, ad hoc, varies	38 product categories
Environmental Product Declarations for UK manufactured construction products	Voluntary assessment documenting the material makeup and environmental performance of UK produced products in line with EN 15804.	J. Anderson	Varies	UK	Quarterly	Product type, EPD Programme
International Dismantling Information System (IDIS)	Information on the material makeup of passenger vehicles subject to end of life vehicle regulations.	IDIS	Unknown	Global	1974-2022, ad hoc, varies	200,000 vehicle parts 3,350 models, 84 car brands
Disassembly-based bill of materials data for consumer electronic products	Collated data on the material makeup of a group of consumer electronic products.	Babbit *et al.* (2020)	%, mass	Global	1986-2016, ad hoc, varies across models	25 product groups, 95 individual models
PROSUM Uban Mine Platform	Products placed on the market, stocks, composition and waste flows for electrical and electronic equipment (EEE), vehicles and batteries.	ProSUM project	Mass, number	EU-28, Switzerland, Norway, Iceland	2001-2020, no longer updated,	Material groups: Vehicles, Batteries, EEE Components/materials/elements Placed on market/in stock/leaving stock

Limited availability of BoM data in many product areas creates somewhat of a challenge for tracing flows and stocks of materials from a system overview perspective. In addition and at a more transaction-level, it can also undermine the extent to which latent value in waste materials at end-of-life might be identified by stakeholders and retained within the economy (Sileryte *et al.* 2022).

Material, component and product flows and stocks

Flows and stocks

Our search identified a range of sources capturing physical data on raw material and semi-finished and finished product flows and stocks in the UK economy. These were found to present data at different levels of aggregation ranging from broad functional areas of consumption e.g. transport or clothing to individual products by brand or model. 'Circular-based goods' are often thought about as those which are recycled, pre-used, by-products, end-of-life or circular manufacturing-based outputs (Corneille and Mizunuma, 2022). While paying particular attention to the coverage of data relating to these, we sought to identify data on products across the board, and have categorised them by broad value chain stage whilst recognising several sources provide cross-value chain insights e.g. trade data.

Inflow

Table 3 outlines several of the data sources identified through our search relating to the physical volume of flows of raw materials, components and products up to the point of consumption in the UK and England. This covered data captured at various points along the value chain, including extraction, imports, retail and consumption.

Table 3. Data assets relevant to the upstream phase of material/product flows and stocks

Data asset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
World mineral statistics	**Extract:** Production statistics for more than 70 mineral commodities by country worldwide, including the UK. Expanded on by the UK Minerals Yearbook specific to the UK minerals industry which captures information on extraction and processing of ~100 materials.[28]	British Geological Survey (BGS)	Metric tonne	50+ countries, incl. UK	1913-2020, annual, 1.5	50 + countries; 70 mineral commodities
Agriculture in the UK	**Extract:** Livestock numbers, prices, production of key commodities and overseas trade.	Department for Environment, Food and	Metric tonne, count	UK: countries, regions	1973-2021, Annual, 0.5	Crops (12+ types), livestock (6+ types)

[28] Data collated by the US Geological Survey (USGS) and World Mining Database (WMD) extend this source into other geographical areas, materials and levels of detail.

		Rural Affairs (Defra)				
Forestry Statistics	**Extract:** Statistics on woodland area and planting, timber and trade.	Forestry Commission	Metric tonne	UK: Wales, Scotland, N. Ireland, England	1976 -2021 (varies), Annual, 0.75	Timber: Softwood/hardwood. Production/ deliveries/consumption by sawmills, consumption, uses
Overseas Trade Statistics (OTS)/Regional Trade Statistics (RTS)	**Import**: Administrative data on volumes of raw materials, semi-finished and finished products imported into the UK and between UK regions.	Her Majesty's Revenue and Customs (HMRC)	Metric tonne	UK	-2022, monthly (OTS), quarterly (RTS)	Up to 8 digit CN codes which are structured to represent in a hierarchical order, product type, material type and production method.[29]
Port and domestic waterborne freight statistics	**Import:** Data about the international and domestic movement of freight by water.	Department of Transport (DfT)	Metric tonne, number	UK	1997-2021, annual, 0.75	Direction Cargo type
International Trade in Services (ITIS)	**Import:** Detailed breakdown of annual trade in UK services[30] estimates, analysing data by country, product and industry.	Office for National Statistics (ONS)	£	UK	2004-2020, annual, 2	Country Product Industry
UK Manufacturers Sales by Product (Prodcom)	**Retail**: Data of businesses in the UK mining, quarrying and manufacturing sectors (SIC Division 8 to 33) regarding the volume[31] (number or mass) of sales of raw materials, sem-manufactured products and final products.	ONS	Metric tonne, number	UK	1993-2021 (1993-2007 not directly comparable to 2008 +), biannual, 0.75 (provisional), 1.5 (final)	~3,800 products (classified under industry classification to 4 digits, and CN extending this - combined Prodcom codes)

[29] The ONS present trade in goods data at a higher level of aggregation and based on the CPA classification in this publication: https://www.ons.gov.uk/businessindustryandtrade/internationaltrade/datasets/uktradeingoodsbyclassificationofproductbyactivity

[30] Excluding travel, transport and banking industries

[31] ONS (2014) highlights possible issues in the reliability of volume-based statistics captured in Prodcom, with figures largely constructed

Annual net additional dwellings and components, England and the regions	**Retail:** Gross change in the size of the dwelling stock due to new builds, conversions and change of use, while capturing net change as a result of the above and demolitions.	Department for Levelling Up, Housing and Communities (DLUHC)	Count	England 9 regions	2000-2021, annual, 0.5	6 components of change
Monthly Statistics of Building Materials and Components	**Retail:** Quarterly data on the volume of sales of sand and gravel, slate, concrete roofing tiles and ready-mixed concrete.	Department for Business, Energy and Industrial Strategy (BEIS)	Metric tonne, Square metre	UK & GB. Geographical detail varies. Most detailed: 9 standard regions & 46 counties	2003-2021, monthly, 0.1	Sand & gravel, slate, concrete blocks, bricks, concrete roofing tiles (production, deliveries and stocks)[32], cement & clinker (production and deliveries)
Waste electrical and electronic equipment (WEEE) statistics	**Retail:** Reports on the amount of electrical and electronic equipment placed on the market by obligated producers under extended producer responsibility regulations.	Environment Agency (EA)	Metric tonne	UK	2007-2022, quarterly, 0.25	14 product categories
Vehicles registered for the first time by body type, make, generic model and model	**Consume**: Number of newly registered vehicles, split by body type, make and model.	DfT	Count	GB/UK	2001-2022, annual, 0.5	6 vehicle types & 445 passenger car makes
England Consumption-based material footprint	**Consume:** The allocation of global primary used raw material extraction to final domestic demand for goods and services by domestic residents.	ONS	Metric tonne	England 15 source county & world regions	2001-2019, annual, 2.5	4 material categories; (England) 7 end use categories; 33 product groups (COICOP), SIC

Across the sources identified, information was captured at different points in the inbound phase, including at the points of domestic extraction or imports, sales/placed on market and consumption and registration. While most were presented on an apparent measurement basis, some sought to account for indirect upstream material flows attributable to those products throughout their supply-chain. Other sources identified through our search capturing data relating to inflows include: on packaging and batteries placed

[32] Detail varies by region of interest.

on the market by obligated producers under UK extended producer responsibility schemes; Wrap's textiles market situation report providing estimates on the volume of textiles placed on the UK market as also incorporated into reports relating to the Sustainable Clothing Action Plan 2020 and Textiles 2030 initiatives; and the 'Carrier bag charge: summary of data in England' published by Defra which captures information submitted to government regarding the number of single-use plastic carrier bags issued/charged for by obligated retailers.[33]

Use

Questions related to the use-phase include what percentage of future demand can be met by materials currently in the stock and when are these likely to become available. In Table 4, we outline data sources identified through our search relevant to the use phase by capturing information on: 1) the quantity and quality/condition of current stocks and lifespans (a key factor influencing the stock level); 2) activities contributing to use phase extension such as repair and maintenance; and 3) product characteristics enhancing the *potential* for these to be undertaken, such as ease of disassembly.

Table 4. Data assets relevant to the use phase of product flows and stocks

Dataset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
Vehicles at the end of the quarter by licence status, body type, make, generic model and model	Count of licensed vehicles at the end of the quarter.	DfT	Count	GB/UK	1994-2022, annual, 0.5	Vehicle body type Make & model Year of manufacture
Council Tax: stock of properties[34]	Count of properties by Council Tax Band at various geographic levels together with breakdowns by property type (including bedroom count) and build period.	Valuation Office Agency (VOA)	Count	England & Wales Region	1993-2022, annual, 0.25	Property type, build period
English Housing Survey data	Age/size of WC cistern and age of bathroom and kitchen amenities based on sample of dwellings.	DLUHC/ MHCLG	Count	England	2008-2020, annual, 1.5	WC Cistern Age (4 categories), bathroom & kitchen amenities age
Electrical products data tables	Modelled estimates for the number of appliances owned by households in	BEIS	Count	UK	1970-2021, annual, 1	Up to 49 appliance categories

[33] Sources maintained by non-UK specific actors include COMTRADE, a multi-country repository of official international trade statistics and relevant analytical tables maintained by the United Nations (UN) and the International Monetary Fund (IMF) Direction of Trade Statistics database.

[34] https://www.gov.uk/government/collections/dwelling-stock-including-vacants

	the UK including stocks of certain non-domestic appliances.					
Electric vehicle charging devices by local authority	Observed number of publicly available electric vehicle charging devices by local authority.	DfT	Count	UK	2015-2022, 0.5, annual	Total/rapid charger split
Non-financial business economy, UK: Sections A to S	Captures monetary data on turnover, employment, input costs and approximate GVA for UK businesses in the production, construction, distribution and service industries (~2/3rds of economy),[35] covering some maintenance and repair activities.	ONS	£, count	UK	1997-2020, annual, 1.5	4 digit SIC 2007, 2 digit when broken down by region/country. Further breakdowns available from publisher on request
Construction industry output data	Construction output in GB covering repair and maintenance activities by the private and public sector and for housing and infrastructure.	BEIS	£	GB	1997-2022, monthly, 0.2	Sector and building type
Open repair data	Records of products brought to repair sites (including those in the UK), whether a repair is attempted, its success, and reported product age at time of (attempted) repair.	Open Repair Alliance	Count, Year	Multiple countries (23), including 16,000 records in GB	2012-2021, ad hoc, varies	product category (40), brand (25), year of manufacture
iFixit repairability scores	Expert-based repairability scores between 0-10 for smartphones, laptops and tables.	iFixit	Score	Non-specific	2007-2021, ad hoc, varies	Brand, model

With physical data on the use phase of materials and products generally sparse and frequently estimated using either: approximation methods drawing on information on inflows and expected lifespans; or being calculated as a statistical balancing item; this was broadly reflected in our review, with observed use-phase data found specific to only a few product-groups (particularly dwellings and vehicles) where statistical registration systems exist. Published modelled estimates were also identified in the case of electronic products. Additional sources identified as providing potential information on the product use

[35] Excludes agriculture, financial activities, public administration and defence, household activities and those of extra-regional bodies.

phase included the BEIS maintained UK Renewable Energy Planning Database and Regional Renewable Statistics Installed Capacity.

Downstream

Waste can be defined as any substance or object that the holder discards or intends or is required to discard (2008/98/EC) and which may be generated during the extraction of raw materials, the processing of raw materials to intermediate and final products, during their consumption and at end of life (Eurostat, CEPA). Table 5 gives a subset of the significant number of data assets identified through our search as providing information on the volume of raw materials and finished product flows through downstream or post-use phases. This includes at the stages of: waste collection; exports; entering managed waste treatment in a differentiated or undifferentiated form (whether for final disposal or treatment through reverse loops such as recycling to be retained within the domestic economic system); or leakage into the environment via unmanaged routes (e.g. illegal waste deposition).

Table 5. Data assets relevant to the downstream phase of material/product flows and stocks

Dataset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown[36]
UK statistics on waste	**Generation and treatment:** Figures compiled on the generation and management of UK waste including waste generation and treatment by EWC across all sectors.	Department for Environment, Food and Rural Affairs (Defra)	Metric tonne, rate, count	UK, England, DAs	2010-2021, annual/biennial, varies	*Generation:* Broad sector, NACE (17 sectors), European Waste Catalogue code (EWC), haz/non-haz *Final treatment:* Recycling rate for households, recovery for construction & demolition and packaging. 6 treatment routes[37] by EWC
Local authority collected waste statistics	**Generation and treatment:** Statistics collated through the WasteDataFlow system regarding the collection and management of waste under the possession or control of local	Defra	Metric tonne	England (Regions & LAs)	2000-2021, annual, 0.5	Waste collection (6 categories of source - 4 household, 2 non-household), waste treatment (5 categories)

[36] Figure in brackets indicates number of categories

[37] Energy recovery, incineration, Recovery other than energy recovery - Except backfilling, Recovery other than energy recovery - Backfilling, Deposit onto or into land, Land treatment and release into water bodies

	authorities in England.[38]					of which dry recycling (8 material categories)
Waste data interrogator	**Transfer and treatment:** The quantities and types of waste that operators of regulated waste management facilities (such as for final treatment or waste transfers) deal with.	EA	Metric tonne	England, NUTS 1, NUTS2, Local authority district, Easting/Northing, postcode Recorded origin: county/town	2006-2021, annual, 1	Waste received/removed Waste form EWC code/Substance-Oriented Classification (SOC) code Fate R&D code
Hazardous waste data interrogator	**Transfer and treatment:** An aggregated high level summary of all the hazardous waste movement notifications in England.	EA	Metric tonne	England, former English government planning regions (13)	2006-2021, annual, 1	Arisings region - district, EWC code, waste fate, deposit region - district
Incineration Monitoring Reports	**Treatment**: Collated annual incineration monitoring reports submitted by operators of permitted waste incinerators to the EA to show if the site has complied with its environmental permit.	EA	Metric tonne	England, former English government planning regions (13)	2015-2020, annual, 1.5	Waste types received (7), waste disposal & recovery (3), raw material usage (7)
International waste shipments exported from/to England	**Exports**: Records of International shipments permitted under the Transfrontier Shipment of Waste Regulations 2007.	EA	Metric tonne	England	2010-2022, annual, 0.1	Country of import, exports 2 main products (RDF, SRF)
Overseas Trade Statistics (OTS)/Regional Trade Statistics (RTS)	**Exports:** Administrative data collection on volumes of raw materials, components and finished products imported into the UK and between UK regions.	HMRC	Metric tonne	UK	-2022, monthly (OTS), quarterly (RTS)	Up to 8 digit CN codes which are structured to represent hierarchically, product type, material type and production

[38] Raw dataset with greater detail can be found here: https://data.gov.uk/dataset/0e0c12d8-24f6-461f-b4bc-f6d6a5bf2de5/wastedataflow-local-authority-waste-management

						method.[39]
National Household Waste composition 2017[40]	**Collected:** Provides estimates of the makeup of household and local authority collected residual waste in the UK.	Waste and Resource Action Programme (WRAP)	Metric tonne, %	UK	2017, ad hoc, 2	Region: UK, England, DAs, London; 55 product and material categories
Annual net additional dwellings and components, England and the regions	**Generation:** Gross and net change in the size of the dwelling stock due to new builds, conversions, changes of use and demolitions.	DLUHC	Count	England 9 regions	2000-2021, annual, 0.5	6 components of change
Food waste statistics	**Generation:** Statistics on food waste generation across household and commercial sources.	Wrap	Metric tonne	UK	2007-2018, Courtauld reporting dates, 2	4 secor-level sources
National packaging waste database (packaging reports)	**Generation, treatment and exports:** Used by obligated businesses and compliance schemes to register with DA-level environment agencies and for preprocessors and exporters to submit quarterly returns on the PRN system.	EA	Metric tonne	UK	2007-2022, monthly (,0.1)/quarterly, 0.25	Treatment type: (Recycling by 8 packaging types); and recovery
Waste electrical and electronic equipment (WEEE) statistics	**Collected and treated:** Reports on the amount of electrical and electronic equipment placed on the market by obligated producers under extended producer responsibility regulations.	Environment Agency (EA)	Metric tonne	UK	2007-2022, quarterly, 0.25	14 product categories
Fly-tipping incidents and actions taken in England	**Illegal deposition:** Figures on fly tipping incidents and actions taken reported by local councils.	Defra	Count	England	2007-2021, annual, 0.5	Incidents & actions; LAs; Waste type (15); Land type(10), size (7)
Waste crime summary	**Illegal deposition:** Tracks identified (high	EA	Count	England	2009-2021, annual, 0.75	IWS (9 categories),

[39] The ONS present trade in goods data based on the CPA classification in this publication: https://www.ons.gov.uk/businessindustryandtrade/internationaltrade/datasets/uktradeingoodsbyclassificationofproductbyactivity

[40] This updates similar work undertaken in 2006-7 by Resource Futures 'Municipal Waste Composition: A Review of Municipal Waste Component Analyses'' and in 2011, 'Detailed compositional assessment for municipal residual waste and recycling streams in England'.

	risk) illegal waste sites (IWS), illegal dumping (12 categories) and illegal exports.					Illegal dumping (12 categories)
KBT Litter Composition Survey	**Illegal deposition:** Provides data on the composition of litter across the UK, including by litter types and brand, with splits for dropped vs. binned litter.	Keep Britain Tidy	Count, %	UK	<2020, ad hoc,	Litter type (17 categories) Detailed product and brand categories
Property crime tables	Provides a range of data on the count of reported metal theft across regions.	ONS	Count	England & Wales	2013-2022, annual, 1	Infrastructure/non-infrastructure
A Study into Second-hand 'Bricks and Mortar' Sales of Electrical and Electronic Products in the UK	A limited UK-wide field study of 'bricks and mortar' second-hand electrical appliance sales.	BEIS	Count	UK, selected regions	2019, ad hoc, 2	Product category, sales outlet/type, condition

Box 2. Predominant classifications in identified waste statistics

The Waste Framework Directive (WFD), transposed into UK law via the Waste (Circular Economy) (Amendment) Regulations 2020, defines when a material should be classified as a waste and how to treat it. Across data assets identified through our search capturing information on the generation and treatment of waste, a range of classifications were found to be in use, with some more predominant than others. As part of 'duty of care' requirements stipulated under the Environmental Protection Act 1990 and Waste (England and Wales) Regulations 2011, when transfers of hazardous and non-hazardous waste take place between entities in the UK (though not applying to transfers made by household sources), these must be tracked using 'hazardous/special waste consignment notes' and 'waste transfer notes', respectively. An excerpt from the Waste (England and Wales) Regulations 2011 below outlines which type of information must be recorded when transferring controlled wastes:[41]

> 35.—(1) This regulation takes effect as if it were made in exercise of the power in section 34(5) of the Environmental Protection Act 1990.
> (2) When controlled waste is transferred in accordance with section 34(1)(c) of that Act the written description of the waste ("the transfer note") must—
> > (a) identify the waste to which it relates by reference to the appropriate codes in the List of Wastes (England) Regulations 2005(b) or, as the case may be, the List of Wastes (Wales) Regulations 2005(c), give a description of the waste and state—
> > > (i) its quantity and whether it is loose or in a container,
> > > (ii) if in a container, the kind of container,
> > > (iii) the time and place of transfer, and
> > > (iv) the SIC code of the transferor;

[41] Waste duty of care: code of practice. https://www.gov.uk/government/publications/waste-duty-of-care-code-of-practice/waste-duty-of-care-code-of-practice

The 'List of Waste' classification, otherwise known as the European Waste Catalogue (EWC) coding scheme, provides a 6 digit hierarchical standardised legal classification system for describing wastes. The classification is used across waste transfer notes, consignment notes and waste data returns to support proper and efficient waste management such as preventing the reuse or recycling of hazardous waste (Sander *et al.* 2008).[42] In its current form, the LoW consists of over 800 codes (6-digit) divided into 20 chapters (two-digit) which are updated periodically. To designate a waste using a LoW code (chapter headings for which are outlined below), a regulated waste holder may first be able to identify the waste in question by the type of industrial process or business activity giving rise to it, with Chapter 01 to 12 and 17 to 20 from the waste chapter codes referring to industry processes and municipal wastes in this way. If no appropriate entry is identified via this route, waste might alternatively be identified more generically by its type (as captured by chapters 13 to 15) and failing this, chapter 16 captures a range of general wastes. If no appropriate code is identified through this process, a waste can then be categorised as unspecified.

A spectrum of issues with the EWC classification ranging from general structural deficits to problems with specific codes were identified in a survey of EU countries in 2008 and these appear to remain largely valid today (Sander *et al.* 2008). Identified issues include:

1. **Inconsistencies in the classification procedure**: Classification problems result from the mix of the waste origin-based approach and the material based approach, including due to inconsistencies in chapter 20 which covers waste from households and commercial and industrial sources but does not cover a material-based approach, leading to ambiguities;
2. **Unclear or imprecise code definitions**: particularly in chapter 19 and for 19 03 'stabilised and solidified wastes', leading to frequent misclassifications; and
3. **Multiple codes existing for what appears to be one type of waste**: Examples include glass packaging, which can be classified by 15 01 07 or 20 01 02, or solid oil wastes which can be classified by 13 08 99 or 15 02 02*

The simple nature of much of waste being unsegregated, the misclassification of waste and the widespread use of undifferentiated (in terms of materials) codes adds to difficulties in tracing materials at end of life at this time. In addition, whilst hazardous waste consignment notes require waste to be attributed to source processes using an SIC code,[43] this information does not appear to be collected for non-hazardous waste (Defra, 2022) as part of waste returns made to the Environment Agency meaning it is therefore not captured in key waste treatment statistical publications such as the 'Waste data interrogator'.[44] While some insight is given into waste by its generating activity through the LoW classification itself, this is not always consistent and a production unit may need to classify its waste under several chapter codes.[45] This presents an issue of being able to attribute waste to sources at present, which is planned to be tackled under the Digital Waste Tracking system scheduled for introduction in the UK from 2023.

A significant number of data assets were identified giving insight into flows of materials, components and products through regulated and unregulated waste systems. Gaps included product-specific data on waste across pre-consumption processing steps (with exception for estimates made regarding textiles by Wrap) and for many reverse loops (UNECE, 2022). A variety of issues in the ease with which materials could be traced at end of life could be seen, including in some cases inconsistencies in identifiers and terms for waste flows and treatments, irregular updates, reporting gaps through exemptions (of which there are approximately 60 different types and 500,000 registered exemptions) and variations in reporting

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[42] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1021051/Waste_classification_technical_guidance_WM3.pdf

[43] While in instances of the wastes on a note being produced by more than one process, current government guidance recommends using the SIC code that produced the majority of the waste.

[44] https://www.gov.uk/government/publications/waste-returns-email-spreadsheet

[45] For instance, a vehicle manufacturer may need to select codes in chapter 8 for wastes from the use of coatings, chapter 11 for inorganic wastes containing metals from metal treatment and the coating of metals and chapter 12 for wastes generated from shaping and surface treatment of metals.

requirements across waste sources and types (Defra, 2022).[46] Additional data not captured through our search but known to exist included: reports by Valpak on material flows for specific materials such as electronics or wood.

Product/material

Recycled content

With limited coverage in production statistics, poor demarcation in trade statistics while notwithstanding several regulations being in place requiring this information to be reported on to the government, limited data was identified through our search on secondary material flows and stocks at the inflow stage. For instance, the UK Aggregates Levy places a charge at the point of first commercial exploitation on primary aggregates imported into and extracted within the UK.[47] Data on secondary and recycled aggregate flows is therefore understood to be collected by UK tax authorities on an ongoing basis, though this was not found to be made publicly available at the time of writing. The Minerals Product Associations' 'Profile of the UK Mineral Products Industry' publishes estimates of secondary aggregate inflows (including as a share of total aggregate sales in Great Britain) though does so on an ad hoc basis. Additional sources identified include the Construction Resources and Waste Roadmap which provides information on recycled content in the construction sector, though at the time of writing, these estimates are likely to be somewhat out of date having been published in 2008.[48] Given this, data where available on end-of-life treatment fate capturing recycled flows may need to be used as a proxy.

Chemical pollutants

Chemicals are sought to be regulated for the environmental and health risks they pose. A robust chemical identification regime is imperative in the context of increased secondary material flows due to the potential for heightened material purity variability risks. Under the EWC classification scheme, hazardous wastes are required to be appropriately demarcated to parameterise potential onward uses. A range of further regulations exist in the UK to limit the introduction of harmful chemicals onto the market. Regulation (EC) No 1907/2006 - Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) which entered into force in the EU in 2007 sought to provide an encompassing regulatory framework enabling information production and risk-controlling decision-making relating to all chemicals produced and/or circulating in the EU market. Following the UK's EU Exit, the UK has established its own 'UK REACH' system grandfathering in some EU authorisations. UK chemical authorisation data which is now compiled by the UK Health and Safety Executive (HSE), sets out: the substance in question for which an application has been made; the applicant; the 'use applied for'; the authorisation opinion status;

[46] The 2022 Defra Waste Tracking consultation proposes a significant overhaul of many of the processes generating data on waste in the UK at present in order to better (more comprehensively, consistently and in real-time) capture the full journey of waste from the point it is produced and transferred to when it reaches its end fate (including end-of-waste and re-entering the economy) and digitalise and centralise this data, including through the use of an open data standard. It is expected the associated data collection system will supersede many of the reporting procedures underpinning the sources identified through our search and is likely to have implications for which data assets will be most relevant to tracking the circular economy going forward.

[47] Under the Levy, exemptions are made for certain secondary by-products and recycled aggregates, though reporting is still required on these by firms registered for the Levy.

[48] As regulatory instruments seek to drive increases in recycled content in a wider number of areas e.g. the Treasury's recently introduced Plastic Packaging Tax, data on the recycled content at the inflow stages are expected to grow. Ensuring openness in measurement methodologies and data outputs associated with these regulations can improve the information base for measuring and modelling recycled/secondary inflows in the UK economy going forward.

and an additional list of descriptors linked to each public consultation which includes expected tonnages onto the market.

In addition, the 2012 EU "Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (EEE) Regulations" which has been retained in UK law, requires manufacturers and importers of EEE, cables and spare parts to ensure components and products placed on the market do not exceed maximum prescribed levels for several hazardous substances. Compliance is required to be demonstrated through means including documentation of testing reports which must be made available on request to the regulator (though do not appear to be made publicly accessible) in addition to affixing a mark to goods sold. While this might imply products falling within the scope of the regulation can be assumed to not breach the prescribed thresholds, potential non-compliance needs to be considered.

A testing regime plays an important role in excluding problem chemicals and mitigating against associated risks. Such problem chemicals have been identified in UK plastic flows (Gerrasimidou *et al.* 2022) and more widely. Notwithstanding consumer safety regulations in place which have sought to reduce/eliminate problem chemicals in products through periodic testing, a 2020 FOI request by the NGO Unchecked UK indicated there has been low levels of testing historically (with this responsibility having previously largely fallen to local trading standards authorities) for the presence of hazardous chemicals above legal limits in consumer goods. Data published by the recently established Office for Product Safety and Standards (OPSS) which now has a role in market surveillance and the stated responsibilities of which include 'regulating chemical hazards in products' (NAO, 2021), captures information on specific products for which safety alerts, reports or recalls have been issued including for reasons of unsafe levels of specific chemicals. The search term 'chemical' brought up 44 such instances of recalls or warnings since the start of 2021 within the OPSS database in relation to specific products. It is understood that testing is also undertaken by authorities regulating imports, however data were not identified capturing results of this from our search. In a context of a more circular economy wherein materials not currently determined to be hazardous in their own right e.g. paper or plastic, carry greater risk of contamination, further consideration of how best to mitigate against this via a more developed testing regime is likely needed.

Recyclability

Outside of sources tracking process-level efficiency rates at end-of-life such as reported under the Environmental Permitting (England and Wales) (Amendment) Regulations 2014 (Schedule 9A - the 'MF Regs') for material recovery facilities (MRF) or recycling rates for some waste streams (e.g. in UK Statistics on Waste or LACW statistics), relatively limited data was found on product-specific characteristics relating to their potential to be incorporated into the economy at downstream phases through recycling. Sources of data which provide material or product-breakdowns can give relevant insight into compositional change within a product-group, including potentially towards materials associated with greater recyclability or lesser heterogeneity. For instance, volume data on packaging published by the EA is split by 9 broad material categories (with approximately 30 more detailed categories below this) for which achieved recycling rates are also published. More sporadic waste composition studies such as that published by Wrap offer greater levels of product/material detail for undifferentiated wastes, with Defra having drawn on this source to estimate avoidable waste entering the residual waste stream (Defra, 2020). It is expected that forthcoming regulatory change such as Defra's updated Extended Producer Responsibility scheme for packaging which plans to incorporate fee modulation based on recyclability criteria may add further relevant data in the future.

In a context of other countries such as France having introduced mandatory firm reporting to populate a product repairability index[49] based on the availability of documentation, ease of disassembly, the availability and price of spare parts and other product-specific aspects (applied to smartphones, laptops, televisions, washing machines, lawnmowers), the current work of Defra and Wrap to explore product-labelling approaches for material efficiency performance (Defra, 2018) may also see data on product-design components enabling potentially higher-value-retaining reverse flows, to further improve going forward.

Impacts

While the volume or mass of materials used can sometimes be considered a proxy for environmental impacts, two materials with significantly different environmental profiles cannot meaningfully be compared on the basis of mass alone (UNEP, 2010). For instance, metallic minerals make up a relatively small proportion of global material use, but by tonne, have a disproportionate environmental and health impact relative to other materials (UNEP, 2013). As a result, there has been a growing emphasis on moving beyond mass-based measurement to drive better environmental decision-making and performance in recent years (Defra, 2018). The environmental impacts of materials and products can be estimated in different ways. This includes using 'bottom-up' approaches drawing on impact coefficients, 'top-down' approaches apportioning a larger total impact to individual products via a variety of methods and hybrid methodologies integrating components of both. Roughly along the same lines, a distinction exists in the boundary of impact between assessment approaches capturing environmental impacts over a product's lifecycle (which can arise over multiple years), versus those tracking impacts in a discrete time period (ONS, 2005).

Life cycle impact assessments (LCIAs), which generally take a 'bottom-up' approach while attempting to capture impacts across a product lifecycle, have become increasingly harmonised in their methods in recent years (including in line with key standards such as ISO 14020-14044) though remain somewhat unstandardised and incomparable.[50] An LCIA involves the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle/value chain (EC, 2021). Data input requirements for an LCA include material sources, manufacturing losses and their treatment and efficiency measures. Assessments are typically conducted using publicly (e.g. IMPACT World+) or commercially (e.g. EcoInvent, GaBi or SimaPro) available tools which draw on libraries of data allowing values from primary research to be transferred to new studies. These libraries of primary data can also be made available on either a public or commercial basis and might include data on completed LCIAs for specific products[51] or alternatively provide impact characterisation coefficients to be applied on a 'look-up' basis to a bespoke inventory mapping of physical inputs and outputs associated with a product within a defined system boundary.[52] Our search identified some collections of impact coefficients also made available by public actors such as the UK 'government conversion factors for company emissions reporting' designed to be used in conjunction with a range of activity data for estimating scope 1-3 emissions in a given period (year).

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[49] Planned to be augmented by a durability index by 2024.

[50] Wiedmann *et al*. (2006) highlights that the comparability of studies on which LCIAs are based is frequently undermined by differences in their material and product coverage, region, source data and time period.

[51] Given the diversity of products and heterogeneity in how these can be sourced and produced, a high level of error can be introduced by transferring values at the level of a product. It is therefore usually done at the level of specific materials and other areas of detail such as region of production.

[52] A prominent critique of LCI-based approaches to estimating environmental impacts of products/activities is the high potential to underestimate these due to truncation errors arising due to arbitrary ('functional') system boundaries imposed to make assessment manageable, with these particularly problematic in contexts of complex supply chains.

Table 6. Data assets identified relevant to estimating physical life cycle impacts

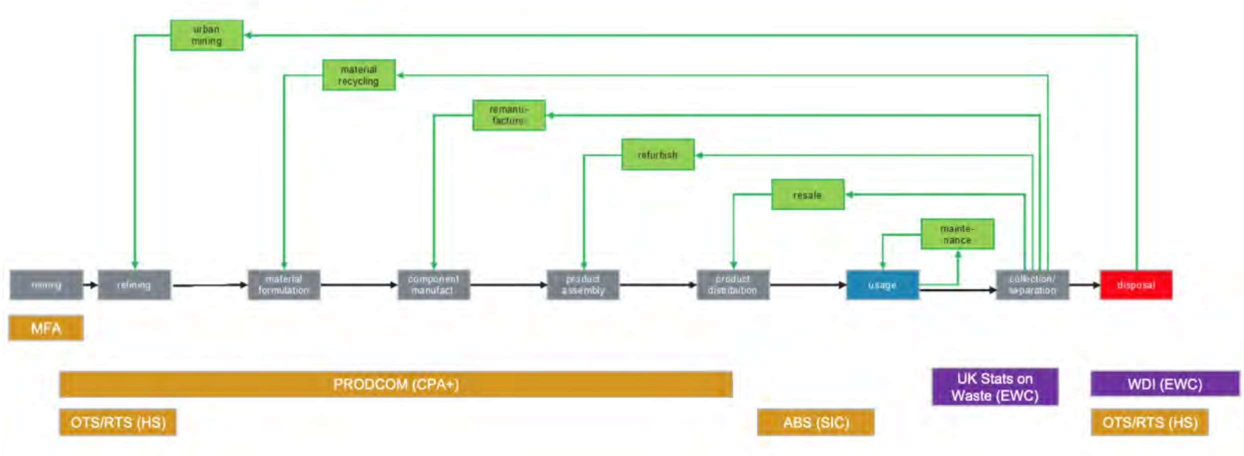
Data asset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
IMPACT World+	A midpoint-damage framework accounting for spatial variability with four distinct complementary viewpoints to present an LCIA profile (Bulle *et al.* 2019)	IMPACT World+	Various impacts	Multi-country		4 LCIA perspectives
Government conversion factors for company emissions reporting	Factors which can be applied to activity data e.g., tonnes of waste disposed to estimate associated scope 1, 2 and 3 greenhouse gas emissions.[53]	BEIS	Kg CO2e	UK	2002-2021, annual, 0.1-0.5	Scope 1 factors: 6, scope 2 factors: 5, scope 3 factors: 21. Condensed and more detailed set
Carbon WARM factors	Conversion factors to enable users to express waste management tonnage data in terms of their Greenhouse Gas emissions relative to landfill.	Wrap	Kg CO2e	UK	ad hoc	12 material categories, 7 treatment routes

Summary

With no source identified through our search capturing data on any individual product (let alone multiple) across all stages of its value chain, the various sources presented here and existing across stages could be considered for use in conjunction with one another to provide this comprehensive picture. Figure 4 presents graphically how several of the outlined data sources in this section give insight into different parts of the value chain.

Figure 4. Tracing material flows across the CE-Hub value-chain taxonomy using existing data sources

[53] Does not apply to to negative emissions technologies and offsets.



Though none insurmountable, attempts to trace products and materials in this way brings up several barriers, with data coverage found to vary across value-chain stages and product groups, boundaries of measurement and in the classifications used by sources for describing similar things. Taking each in turn, a limited amount of data was found in relation to product stocks, while there were significant gaps in data tracing flows through many reverse flows (particularly outside of recycling) for a large share of the national waste stream. In addition, for some product groups such as buildings/dwellings and vehicles, there was greater data coverage overall but different levels of detail captured across groups. Figure 5 presents the number of data sources identified through our search across several key product groups and value chain stages, with a product-level example (electric vehicles) and a component within this (rare earth permanent magnets) illustrated.

Figure 5. Identified assets providing data on product flows and stocks in physical units across value chain stages[54]

	Inflow	Use[55]	Outflow and reverse flows
Construction	6	2	8
Vehicles	4	1	7
Electric vehicles	1	1	0
REE-Ms	0	0	0
Electronics	4	1	8
Packaging	4	0	8
Textiles	3	1	7
Food	2	0	6

[54] These sources may not be specific to, or comprehensive of, each of these product groups and value chain steps listed, but rather capture information *relevant* to them.
[55] We do not include data assets capturing activities and characteristics contributing to extension of the use phase here to best reflect data on physical/volume flows.

Furniture	3	0	3

Measurement boundaries were found to vary across sources identified, with the majority presenting figures aligned with an apparent or direct measurement boundary and only the consumption-based statistics seeking to track upstream material flows associated with (final demand for) particular product groups. Differences in classifications additionally complicate tracing materials and products across value-chain stages by making it difficult to establish if two categories refer comprehensively and coherently to the same thing, though bridging these is again possible. Greater consistency can reduce ad-hoc bridging and make assessment and tracking more consistent.

The combined overall variability and patchiness of publicly available data along these lines renders the process of tracing flows and stocks for many key materials and product groups in the UK at present quite difficult. A range of issues in quality and accuracy of data have also been noted e.g. the ONS (2014) highlights possible issues in the reliability of volume-based statistics captured in Prodcom.

2.3 Activity layer

Examples of stakeholder questions relating to layer

1. *Who are the key actors involved in a given value chain, their location, and the number of profit margins that might be affected by more circular production methods and consumption patterns?*
2. *What is the value proposition of more circular business models to firms along the supply chain?*
3. *At what point might increased raw material prices make the remanufacturing of goods more economically advantageous than the current more linear treatment of materials?*

A raft of studies have pointed to the potential or realised microeconomic benefits to firms and market-actors more broadly through the more circular and efficient treatment of materials. Benefits have been argued to (potentially) emerge through routes such as: cost reductions, including from no/low-cost investments (Oakdene Hollins, 2007; 2009; 2017; Baptist and Hepburn, 2013; Wrap, 2016; Oswald, Whittaker and Hilton, 2018); lessened exposure to price fluctuations, associated capital risk premiums and hedging costs (Lee *et al.* 2012); improved competitiveness of the macroeconomic environment (Flachenecker, Bleischwitz and Rentschler, 2016); lower compliance burdens; and product differentiation advantages (Porter & van der Linde, 1995; Ambec and Lanoie, 2008). Change in operations along value chains can nevertheless require up-front investments which may be associated with opportunity and lending costs and have implications for financial variables such as capital and operating expenditure, revenues, profit margins and cash flow profiles.

The next layer of assessment in the observatory analytical framework therefore involves testing the financial feasibility and economic implications of change in a value chain towards greater circularity. Adding to biophysical product-level analysis outlined in the prior layer, such assessments are critical as firms often remain undecided about the extent to which more circular business models are financially viable (Kambanou and Sakao, 2020).

Primary analytical methods employed at this level include: entity/stakeholder mapping and value chain analysis; activity costing; financial and social cost-benefit analysis (CBA); and where required, geospatial assessment. Exploring each in turn, stakeholders and their associated activities along a value chain must firstly be identified and mapped out to determine the number and nature of associated logistics steps and profit margins that changes to enable greater circularity (e.g. achieving improved and higher-value cascading options for a material) might reconfigure. Next, current and potential future revenues, costs and profit margins (as well as other relevant financial variables) need to be established and estimated to characterise the current baseline value distribution against which to compare more circular alternatives.[56] In the absence of explicit legislative prohibition, a comparison of wider social costs to benefits coupled with economic balancing is now the default standard [including in the UK] when formulating most new government regulation (Sunstein 2000). Social CBA is distinguished from financial analysis (which compares private revenues and costs) by comparing social benefits and costs to society more widely.

For the alternative(s) models taken forward in an assessment, necessary investments have to be costed out and against-baseline changes in those same financial variables modelled. Accounting for geospatial components is key in many cases as transport costs can be prohibitive to financial feasibility for many

[56] Identifying opportunities for cost-reductions and increases in value can be highly context specific e.g., changes to in-house prototyping practices in an architectural firm or value-chain wide changes to enable greater cascading of steel and construction materials. Therefore, these are identified on a case-by-case basis and a range of alternative options can be explored in terms of feasibility and associated risks.

strategies, particularly those relying on reverse logistics. As well as financial cost-benefit criterion and cost-benefit ratios, metrics such as ROCE can be used here as a basis for the comparison of options. Understanding potential wider social costs and benefits requires expanding the remit of focus to capture wider welfare implications of these changes.

Modelling microeconomic benefits and costs comprehensively when testing option(s) against a baseline therefore requires drawing on a range of information (Flachenecker, Bleischwitz and Rentschler, 2016). This includes on: relevant entities/actors; prices and costs of business model changes; financial variables such as revenues and profits by entities; extra-private economic cost and benefit data and geospatial dimensions. For example, an assessment of the financial desirability of shifts in a value chain involving the substitution of material inputs for labour and capital (or alternatively primary for secondary materials) will depend heavily on assumed future prices for these inputs in addition to the current makeup of revenues, profit margins and spatial dimensions. Further, an assessment of the broader economic desirability of that shift will also rely on data relating to social transactions and externalities. We examine publicly accessible data identified through our search in relation to each of these input requirements below.

Entity mapping

Here, data is sought to help establish the type, size, location and activities of key stakeholders/entities. Core actors along value chains include inbound suppliers and firms (covering stages of extraction, production, manufacture and retail), consumers, outbound logistics and waste companies as well as industry associations. A large share of these core actors can sit outside of UK territory boundaries given the highly transboundary nature of many modern-day value chains. Other actors to map include those in extended networks linked to a value chain, such as technology and service suppliers or certification bodies and entities situated within a wider ecosystem such as government policy and administrative departments, NGOs, consultancies and academic researchers (UNECE, 2021b).

The Companies House service 'Find and update company information' makes available free of charge and without any registration requirements, all public data held by Companies House on limited companies falling within the scope of the Companies Act 2006.[57] This includes on almost 5 million active private and public companies as of April 2022. Through this service, companies can be searched for by, among other fields, name, address, SIC code[58] and company type. Known issues with this source of data include that companies listed as active may in fact be dormant, while registered addresses may correspond to personal addresses rather than the location of a company itself. In addition, Companies House does not verify the accuracy of information filed meaning there are also potential risks around the accuracy of this data.

Several additional sources of data relevant to identifying entities were found through our search. For instance, HMRC collects information on domestic actors registered as being involved in international trade. In addition, the Environment Agency maintains an extensive collection of public registers of businesses involved in regulated industries including waste management. This covers both those who require permits and those who are otherwise exempt from needing to do so due to not meeting a defined reporting threshold. Specific registers are maintained for entities engaged in activities relating to particular

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[57] This is accessible via the Companies House RESTful API, though access via *this* route does require registration.
[58] With the vast majority, but not all, companies using one SIC code to represent their activities (The Data City, 2020).

regulated areas including the management of waste electronics and electrical equipment or vehicles at their end of life.

To get a sense of the scale of activities conducted by these business entities in monetary terms, Accounts Data submitted to Companies House can be used among others e.g. the dataset 'UK Business: Activity, Size and Location' which gives a wider, more aggregated, but potentially still useful picture presented in monetary and employment size terms to a 4-digit SIC level. To gauge the same but in physical terms of material throughput, the Waste data interrogator can be used to better understand the scale of activities undertaken by firms who are engaged specifically in the downstream phase, as can additional data collected by the EA on permitted sites. Table 7 sets out those sources identified as relevant to this input requirement.

Table 7. Data assets relevant to entity mapping at the activity layer

Data asset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
Find and update company information	Makes available all public data held by Companies House on limited companies falling within the Companies Act 2006.	Companies House (CH)	-	UK	Regular ongoing updates	Address, incorporation/dissolution date, status, nature of business (SIC), type
UK Trade Info	UK traders searchable by commodity code, postcode or name.	HMRC	-	UK	Regular ongoing updates	By commodity code, postcode
EA Public Registers	A collection of registers on businesses or individuals permitted (or exempt from these requirements) to undertake activities impacting the environment, including the management of various wastes. Includes locational information for many entities.	EA	-	England	Regular ongoing updates	Operators permitted under Environmental Permitting Regulations; waste carriers, brokers and dealers; scrap metal dealers; WEEE approved compliance schemes, producers, AATFs[59] & exporters
Waste Data Interrogator	Quantities and types of waste dealt with by approximately 6000 regulated sites, including locational information. Adds additional depth to	EA	Metric tonne	England	2006-2021, annual, 1	Received/removed, locational data, fate, SOC codes, EWC codes

[59] Approved authorised treatment facilities.

	waste registers by showing relative scale and active operations.					
Environmental Permitting Regulations - Waste Sites	A quarterly snapshot of effective permitted waste sites in England (+9000). Permitted landfill sites (including those no longer active are captured here).	EA	-	England	1974-2022, quarterly, 0.25	Operator Site address Site type Date permit issued

Notwithstanding the relatively high level of available public data on core entities in value chains within the UK and at its interface with other countries through trade, non-UK domiciled entities are harder to identify through the assets found in our search. This is understandable given their UK-focus. This nevertheless means that an assessment relevant to non-territorial actors will likely need to draw on wider sources of information including company registers in other countries, where available and databases maintained by international organisations. With exception to the highly aggregated inter-industry transaction data captured in the supply and use tables furthermore, limited data was found showing linkages between entities in terms of their transactions, thereby necessitating external knowledge (including potentially from BoM data objects) to piece together which actors make up a particular value chain where greater detail is sought.

Cost analysis inputs

Our review identified several sources of data capturing information on prices which could potentially serve as an input into value chain, financial and social cost-benefit analysis and tracking relevant KPIs at the activity level. A subset of the sources identified and viewed as most relevant to the scope of the 5 centres making up the NICER programme is presented in Table 8.

A large proportion of sources identified were found to present price data in an indexed form with the objective of helping track *change* in prices across frequently a basket of products over a period of time. For instance, data on producer price inflation indices published on a monthly basis by the ONS tracks change in output prices across 24 product groups on one hand and those in input prices across 34 commodity groups and for 45 selected industries covering costs of materials and fuels[60] in line with the CPA 2.1, but does so in an indexed form. Similarly, Defra's 'Agriculture in the UK'[61] compendium provides reasonably detailed price data for agricultural products/commodities, but does so also in an indexed form. For *ex ante* assessment, such an understanding of historic and current price trends are useful as an input into making estimates of the range in potential future prices which can affect payoff structures. However, if reference prices corresponding to the categories, detail and time period captured in the indexed form are not known, these sources and others like them cannot give insight into unit prices which are generally required for assessment at this level. By comparison, ONS consumer price inflation data (published on a monthly basis) includes alongside its indexed form, spot price quotes for the approximately 600 items making up consumer-side inflation indices, while capturing regional heterogeneity in these.[62] As these

[60] Including for 6 metal and nonmetallic mineral products and 7 chemical products.

[61] https://www.gov.uk/government/collections/agriculture-in-the-united-kingdom

[62] https://www.ons.gov.uk/economy/inflationandpriceindices/datasets/consumerpriceindicescpiandretailpricesindexrpiitemindicesandpricequotes

indices are often updated to best reflect current economic circumstances, possible risks of discontinuity in particular price inputs need to be kept in mind.

Other sources identified through our search which provided or could be used to derive similar unit price data included: Prodcom, which by including data on the monetary value of sales alongside product volumes in the UK industrial sectors, allows a measure of sales price per unit to be derived thereby giving insight into *average* costs per product group for a hypothetical purchase from the production sector. The variable presentation of units in volume data need to be kept in mind. Similarly, through incorporating import cost and volume data[63] alongside one another, HMRC trade statistics allows average costs per unit (and with a lesser level of temporal and transaction aggregation) to be estimated for the traded products they capture, including with a greater level of detail. With the substitution of material for labour inputs often central to many circular economy strategies, having an understanding of unit labour costs is likely to also be important for the majority of assessments. The 'Employee earnings in the UK' publication- as the most comprehensive source of data on earnings in the UK, provides basic pay totals to the 4-digit SIC07 level, with regional breakdowns provided at the 2-digit level and a range of additional information supplied in the source.

Though established surveys such as the Annual Purchasers Survey,[64] the Annual Acquisitions and Disposals of Capital Assets Survey[65] and Annual Business Survey (ABS) ran by the ONS all capture data from producers regarding costs such as for the purchase of inputs and employment, this information is not always published in a directly usable form due to aggregation to avoid confidentiality issues. For instance, even when accounting for employment costs being presented separately, the ABS's composite variable 'total purchases of goods, materials and services' for industries up to a 4 digit SIC code are aggregated across these input-types, while insight is not provided into what/from whom purchases consist of. Though the UK SUTs and IOATs give insight into cost structures across industries and products by comparison, these are presented at the relatively aggregated SIC divisional level.

Alongside multiple sources of price index data additional to those described here, further separate sources capturing unit prices were found for certain product groups of strategic importance such as dwellings, fuel and energy and agricultural and timber products, as well as for relevant services such as waste management gate fees. Rates for taxes levied on economic activities e.g. landfilling and primary material excavation or products e.g. VAT by the government are usually published via gov.uk or similarly accessible sources. Price data on secondary raw materials was found to be relatively sparse, with a sole source identified capturing this, the 'Materials Pricing Report', appearing to be restricted in its access to users otherwise able to contribute intel. Additional sources of global commodity price data were not captured by our search approach, but were expected to be of relevance to many assessment cases. Life-cycle costing databases used to support financial analysis of capital expenditures may also offer a source of information relating to whole-life costs of capital investments, though an open access form of such data was not identified through our search. While a more extensive review would be required to confirm this, detailed information on individual firm activity-level costs has remained as closed in-company due, to a large extent, to commercial sensitivities.

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[63] Though not expressing the domestic end use to which these are applied which could help situate prices further

[64] Surveys businesses regarding their purchasing patterns to characterise intermediate consumption including as an input into SUTs and the calculation of the headline macroeconomic statistics of national GVA and GDP.

[65] Surveys businesses regarding capital expenditure across several product groups such as for vehicles, machinery, non-dwelling buildings and intangibly produced assets, intended to feed into estimates of gross fixed capital formation, which are also a key component of GDP. Previously referred to as the 'Business spending on capital items' survey

Table 8. Data assets relevant to price and costs at the input layer						
Data asset	**What does it tell us in relation to this input requirement?**	**Publisher**	**Unit**	**Geographical extent and detail**	**Time covered, update frequency and lag (year)**	**Extra-geographical breakdown**
Price Indices Data	Provides measures of inflation and prices for the consumer price indices, producer price indices and components of these. Spot prices provided for the consumer-side.	ONS	£	UK	varies, monthly, 0.1	Producer: Output prices - 24 product Input prices - 34 commodity groups, 45 selected industries for specific costs Consumer: 600+ items
UK Manufacturers Sales by Product (Prodcom)	Monetary value of sales and volume of products manufactured in the UK mining, quarrying and manufacturing sectors (together industrial sectors).	ONS	£, metric tonne/number	UK	1993-2021 (1993-2007 not directly comparable to 2008 +), biannual, 0.75 (provisional), 1.5 (final)	~3,770 products (interoperable with NACE, CPA, CN), 234 industries
Overseas Trade Statistics (OTS)/Regional Trade Statistics (RTS)	Monetary value and volume of finished, semi-finished and raw material imports to the UK as well as exports.	HMRC	£, metric tonne	UK	-2022, monthly (OTS), quarterly (RTS)	Up to 8 digit CN codes (based on HS up to 6 digits)
International Trade in Services (ITIS)	Detailed breakdown of annual trade in UK services[66] estimates, analysing data by country, product and industry.	ONS	£	UK	2013-2020, annual, 2	Country Product Industry
Employee earnings in the UK	Based on the Annual Survey of Hours and Earnings, captures variables including hourly, weekly and annual pay alongside paid hours worked.	ONS	Hours, £	UK	1997-02 (SIC92), 2003-08 (SIC03), 2008-2022 (SIC07), annual	4 digit SIC basc totals & full-time/part-time splits Basic/overtime split
Price Paid Data	Includes information on all property sales in England and Wales sold for value and	HM Land Registry	£	England & Wales	1995-2022, monthly, 0.1	Locational data Property type Estate type Price

[66] Excluding travel, transport and banking industries.

	lodged for registration with the Land Registry.[67]					Sales date
Monthly Statistics of Building Materials and Components	Contains monthly data on price indices, bricks, cement and concrete blocks; and quarterly data on sand and gravel, slate, concrete roofing tiles and ready-mixed concrete.	BEIS	£, metric tonne	GB	2003-2022, monthly, 0.1	Material
Energy Price Data	Covers energy prices for domestic and industrial consumers and for all major fuels, drawing on Domestic energy prices, Industrial energy prices and Road fuel prices statistics also published by BEIS.	BEIS	£/KwH	UK	2013-2022, quarterly, 0.25 Underpinning data published more frequently	Domestic/industrial/road
Gate Fees Reports	Analyses the gate fees charged for a range of waste treatment, recovery and disposal options as reported by local authorities.	Wrap	£/metric tonne	GB	2006-2022, annual, 0.5	Treatment type Region
Materials Pricing Report	Free subscription service for buyers and sellers of recovered materials to give more information about pricing trends and current conditions in the markets for recovered materials.	Wrap	£	UK	Not known	Not known

Entity/product-level financial data

Our search identified a range of relevant public data sources capturing monetary data on variables relating to the financial performance of private and public-sector entities and the products they exchange. This includes revenue, capital deployed/costs, various efficiency measures and profit for actors along value chains provided at varying levels of detail.

As part of its Accounts Data, Companies House makes business microdata in the form of company profit and loss accounts and balance sheets (containing information on assets, liabilities, capital and reserves) which have been filed electronically with them freely available. This covers approximately 75% of the 2.2 million accounts filed at Companies House each year but does not include revised accounts. The accounts data are prepared to the UK GAAP (Generally Accepted Accounting Practice) standard and the level of detail included in them varies with the legal structure and size of reporting companies (in line with

[67] The ONS also track mean and median house prices.

staggered requirements linked to criteria on turnover, assets and employee numbers).[68] In conjunction with an understanding of which entities make up a given value chain, this can help give insights into profit margins along these. The UK Data Service also provides access to more detailed and 'reasonably identifiable' business microdata across variables including earning, trade, industrial relations and innovation, though by being collected under the Statistics of Trade Act 1947, can only be accessed in a secure setting to ensure confidentiality.

The ABS captures business and financial information from a sample of roughly 70,000 UK businesses grossed to business populations at a 5 digit SIC level. It captures data on variables at these levels of aggregation which include on turnover, expenditures on goods, materials and services (while separating out those relating to employment) and capital expenditure and stocks, from which an approximate measure of GVA (aGVA)[69] in basic prices is made. It should be kept in mind that these financial variables will capture both product & non-product income for firms. Some issues with the ABS include that captured data is collected for a given business as a whole based on their self-described *main* activity and notwithstanding the fact that these entities may undertake a range of activities.[70] In addition and due to the stratified random sample design underpinning the survey, the ONS cautions against treating this data as time series, though in actuality it frequently is e.g. being incorporated into GVA figures.

The Prodcom publication gives insight into turnover by products, helping inform about the relative role of different products in driving industry-level gross output. As costs are not included, profits per product cannot be taken directly from the source, however and will need to be based on assumptions. Some other issues with the source include the relatively small sample for some fairly detailed codes leading to possible issues of spurious accuracy and high levels of suppression in public releases. In addition, its scope being limited to SIC Divisions 8-33 also means data for subsequent divisions e.g. waste collection, treatment and disposal services or materials recovery services are not provided. Tracking both import and export data in HMRC trade statistics gives insights into costs and elements increasing output, respectively. In addition, the Business Register and Employment Survey offers detail on employment statistics (including with public/private, full-time/part-time splits) down to the SIC 5-digit level with further regional breakdowns. These can be used in conjunction with the ABS to estimate the turnover generated per person employed as one variable of financial performance.

Changes in government expenditures such as for household waste management systems may be required to drive greater circularity. While government entities are not usually thought of as having profit margins in the same way businesses do, they nevertheless have revenues and expenses and rationales to ensure the latter are not consistently greater than the former. The source 'Local authority revenue expenditure and financing England' tracks revenue and expenditure data across local authorities with a fairly detailed breakdown including across various forms of waste management costs. Similarly, while households do not generate profits in the conventional sense, higher costs can erode living standards and consumer surplus. The ONS publication 'Family spending in the UK' as part of wider retail sales statistics, tracks household expenditure on an ongoing basis at a detailed level in line with the COICOP classification, while household income statistics are furthermore tracked closely by the ONS.

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[68] For companies with a turnover of less than £10 million, these accounts include asset and liability figures, while for those grossing over £10 million, additional variables such as turnover are reported.

[69] Measured as income minus intermediate consumption of goods and services used to produce outputs, labour costs and operating surplus/loss and effectively approximates profit. Conceptual, coverage and coherence adjustments are made in the publication of industry/national GVA figures measured under the national layer heading.

[70] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/501968/BIS-16-65-AC-manufacturing-metrics-review-annex-c-ONS-manufacturing-sources.pdf

Table 9. Data assets relevant to entity-level financial data at the activity layer						
Data asset	**What does it tell us in relation to this input requirement?**	**Publisher**	**Unit**	**Geographical extent and detail**	**Time covered, update frequency and lag (year)**	**Extra-geographical breakdown**
Accounts Data	Information on profit and loss and assets, liabilities, capital and reserves across at least 1.5 million companies.	CH	£, count	UK	-2022, regular ongoing updates, 1 day	Variables: assets, liabilities, capital and reserves. Vary by company size.
Non-financial business economy, UK: Sections A to S	Monetary data on turnover, purchases, reporting units, employment, input cost, capital expenditure, approximate GVA for UK businesses in the production, construction, distribution and service industries (~2/3rds of economy).[71]	ONS	£, count	UK	1997-2008 (SIC03), 2008-2020 (SIC07), annual, 1.5	4 digit SIC 2007 level, 2 digit when broken down by region/country at ITL level 3.[72]
UK Manufacturers Sales by Product (Prodcom)	Monetary value of sales and volume of products manufactured in the UK mining, quarrying and manufacturing sectors (together industrial sectors) at 8-digit SIC level.	ONS	£, metric tonne/count	UK	1993-2008 (SIC03), 2008-2020 (SIC07), biennial, 0.5 (provisional), 1.5(final)	~3,770 products (interoperable with NACE, CPA, CN), 234 industries
Business Register and Employment Survey[73]	Captures employment figures including part-time/full-time or private/public sector splits.	ONS	Count	UK	-2021, Annual, 0.75 (provisional)	National estimates 5 digit SIC(07)
Overseas Trade Statistics (OTS)/Regional Trade Statistics (RTS)	Administrative data collection on volumes of raw materials, components and finished products imported into the UK and between UK regions.	HMRC	Metric tonne	UK	-2022, monthly (OTS), quarterly (RTS)	Up to 8 digit CN codes
Local authority revenue	Outturn data of local authority revenue	DLUHC	£	England; Local	2007-2022, annual, 0.5	Revenue type

[71] Excludes agriculture, most financial activities, public administration and defence, household activities and those of extra-regional bodies.

[72] Further breakdowns available on request.

[73] Offers a more reliable industry breakdown than the Labour Force Survey as employes do not self-classify themselves to an industry.

expenditure and financing England	expenditure and financing for the financial year.			authority		
Family spending in the UK	Average weekly household purchases in the UK, split by COICOP categories, place of purchase, income decile and age of respondent.[74]	ONS	£	UK	2001-2021, annual, 1	Age, income, economic status, socio-economic class, household composition and region.

Externalities

In an LCIA, categories of impact can be split between mid- and end-points, with midpoints capturing singular dimensions of environmental pressure such as emissions or ozone depletion and endpoints going a step further by attempting to capture the impacts or damages of these pressures such as on ecosystem quality, species loss or human health and wellbeing. Under this language, one way of expressing an endpoint is monetarily in terms of its effects on economic welfare, with externalities referring to uncompensated (in the sense of not being captured in a price) social costs[75] (negative externalities) or benefits[76] (positive externalities) resulting from private economic activities. These benefits and costs will not be known with certainty.

The value of an externality is a function of not only the biophysical characteristics of an impact but too the sociobiological demand context in which it occurs and implicitly, whose welfare is accounted for in an assessment i.e. who has 'standing'. Therefore, sources of data accounting for UK-specific demand profiles or transferable in a way while accounting for demand-side differences (e.g., using a transfer function) can help reduce the introduction of error into an assessment.[77]

Our search identified a limited number of data sources made available on a public basis capturing information on externalities or social costs, with this paucity in part due to the information-intensive nature of producing such estimates. The most readily usable were published by the UK government as part of its supplementary guidance to the Green Book[78] and are provided as coefficients to be applied to midpoint units of atmospheric emissions. Additionally, some historical studies were found which attempted to capture components of the disamenity effects of landfill and incineration, providing coefficients for value transfers which could be applied on a per-tonne or per-site basis (Cambridge Econometrics, EFTEC & WRC, 2003; Havranek *et al.* 2009). While these estimates could be adjusted to today's prices in line with inflation, it is likely the supply and demand-side contexts have changed since these were produced and the values may no longer be as relevant.

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[74] Includes data on household costs for maintenance and repair of households and vehicles.

[75] 'Costs' broadly refers to outputs of a project or programme which decrease human welfare - including input costs. Private costs accrue to those making a product. Social costs include those accruing to the wider society and are a summation of marginal private and social costs.

[76] 'Benefits' broadly are outputs of a project or programme which increase human welfare, the value of which can be assessed based on how much someone is willing to pay for that benefit.

[77] Where available, market prices or adjusted market prices can be used here, and where market distortions exist, a choice must be made between demand or supply prices depending on whether the product in question is an input or output. Where market prices are not available, a range of non-market valuation techniques have otherwise been developed.

[78] The Green Book steers the government's approach to economic assessment and sets out steps to systematically compare social costs and benefits of proposals based on the welfare changes they have the potential to bring about.

With the increasingly prominent framing of the environment as a form of capital given its ability to generate welfare benefits now and into the future, a significant number of tools have been developed to support the valuation of (changes in) natural capital stocks and the ecosystem service flows derived from them. These tools include from the following projects: Artificial Intelligence for Environment & Sustainability (ARIES), Costing Nature and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), and specific to the UK, Natural Environment Valuation Online (NEVO), the Environmental Value Lookup Tool (EFTEC, 2015) and the Enabling Natural Capital Approach (ENCA) resources.[79] Utilising these and others, a large number of scenario-based modelling studies have sought to quantify the economic impacts of changes in natural capital and ecosystem services due to direct and indirect drivers across a range of scales. For many of these tools, their low-levels of spatial resolution as well as difficulties in linking product changes to land-use effects and in turn, natural capital impacts can impede their applicability.

Of the resources listed, ENCA is recommended for use in the 2020 HM Treasury Green Book. It consists of guidance, an assessment template and a compiled database of economic studies to help consider the effects of policies or projects on natural capital. Its application requires an external assessment of the biophysical effects[80] on the quantity, quality and location of natural capital stocks and flows such as due to change in the pressure of resource use, waste production or treatment, followed by an economic appraisal of these effects while drawing on the monetary service values the resource collates. Unlike for globally-intermixing gases, valuations of many natural capital impacts are highly context specific and likely require individualised assessment to avoid high levels of inaccuracy. It is a grey area regarding the extent to which overseas environmental change might be incorporated into an assessment in which those who have standing are delimited as the Uk populace.

Table 10 sets out the publicly accessible data sources identified through our search as giving potentially relevant information regarding externalities. Additional sources of externality data such as those maintained by the organisation TruCost were known to the reviewing team, but fell outside of the scope of this assessment due to only being made available on a commercial basis. Reviewing the academic literature further would no doubt provide additional relevant information and we therefore recognise this is likely to be a limited selection of secondary sources relevant to this layer. We welcome feedback on others.

Table 10. Data assets identified relevant to estimating externalities

Data asset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
Carbon and emission values	Guidance that provides government analysts with a set of rules for	HMT	£/tonne	UK	2020-2050, annual, 1	Atmospheric pollutants: 2

[79] The simplest of these draw on proxy-based approaches such as multiplying a land use or land cover's areas by a unit-to-area value ratio (Potschin, 2009) while others draw on more complex causal relationships and statistical and biophysical models (Petz, 2014).
[80] Biophysical methods assess material and energetic change, valuing stocks, proxies of landscape structure and composition e.g. land cover or constructed metrics e.g. landscape diversity.

	valuing energy usage and greenhouse gas emissions.					
Enabling a Natural Capital Approach (ENCA)	Data, guidance and tools to help users understand natural capital and know how to take it into account.	Defra	£/various	UK	Varies	Asset values Service values

Summary

In relation to the input requirements across the activity layer of the analytical framework, our search identified a range of data relevant to mapping value chain actors and financial assessment of changes in activities and products. Other sources of potential relevance here but not detailed include the ONS publication on 'Business Demography' capturing business births and deaths, Company House's publication 'Incorporated Companies in the UK' capturing (changes in) their company registers and BEIS' 'Small Business Survey' capturing a range of data on the smallest firms operating in the UK. Nevertheless, some of these sources present data at a more aggregated level than for individual firms and in drawing on those, an assumption of homogeneity may need to be made. Given the potential for quite context-specific value chain assessment, such sources present a minimum basis which should be built upon, where possible, with more precise contextual entity-level data where it can be found and accessed.

In light of the current coverage of data, more detailed assessment at the activity layer will likely need to be populated inductively and based on clear assumptions. Some relevant data were thought to be published by firms as part of their regular reporting requirements and could be explored further. Non-domestic actors and value chain steps and activities are a gap across the identified sources and the availability of data across significant trade partners could also be explored more to be able to build up a comprehensive picture of international value chains. Least not because of the resource intensiveness of their estimation, externality-related data was found to be thinly available making it difficult to monetise ascribed potential costs and benefits of an option comprehensively using published data. Where sensible/defensible estimates cannot be made, this can lead to incomplete social cost-benefit analyses.

2.4 Meso layer

Examples of stakeholder questions relating to layer

1. *How many firms can a potential business-model change be relevant to?*
2. *What is the quantity of resource use and waste generated by different industries and sectors? How does this sit in relation to indicators of economic performance?*
3. *What might be the impacts on industry output and value added of increased circularity in production and consumption practices? What is the relationship between these physical variables and financial performance?*

The next layer of the observatory analytical framework involves tracking and appraising (potential) change and impacts at the 'meso' level. Meso broadly refers to any grouping of institutional units between micro and national levels. For assessment and appraisal of outcomes and impacts at this level, data specific to: *institutional sectors,* as grouped in the national accounting system on the basis of their relatively homogeneous functions and incentives e.g. corporations, households or government; and *industries* i.e. detailing further those units within the corporation sector based on their production of similar goods and services, is sought. From an *ex post* perspective, the coverage of data inputs across these meso-level units is broadly examined in terms of whether data was identified on: material and monetary/economic flows and impacts for value chain stages to help us detect, retrospectively, whether greater circularity and sought impacts are materialising while risks and negative impacts are not.

Integrating outputs of preceding micro-level assessments into meso and, in turn, macro-level analysis can strengthen confidence in any outputs of the latter. Methods relevant to *ex ante* assessment at the meso level include assumption-based extrapolation to scale micro-level findings to the number of institutional units to whom a change might be applicable. Change in an industry or sector rarely occurs in isolation however, with firms needing to purchase materials and services from other industries and wider indirect, induced and secondary effects possible across product, financial and distributive transactions.[81] Such secondary effects can be captured in a variety of ways, including and for indirect effects specifically, via the use of multipliers derived from input-output tables.[82]

Alternatively, macroeconometric models (encompassing computable general equilibrium (CGE) and macroeconometric models) also build on IOTs but further seek to incorporate microeconomic theory or econometrically derived parameters to account for the potential impact of price changes. As well as national-level insights, these models can provide outputs to the level of sectors and industries, though the level of detail in which depends on the specifics of the model's inputs and design. Macroeconometric

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[81] The potential for spillovers cascading across economic, social and environmental domains is captured in the following description: ***In physical terms, 'the economy functions through the production [the variably consumptive conversion of production factors e.g., labour, built and human capital] and import of goods and services which are consumed by firms, households or government, exported to the rest of the world or accumulated to be…used…in the future' (SEEA, 2012, p. 12). These physical flows are mobilised by labour and capital inputs, with economic value created through production activities and 'value added' what remains after the costs of production are accounted for. From this residual, income is derived, including [in the form of] wages and share dividends. This income is then either spent or saved as financial or non-financial assets and in some cases re-lent back into the economy (Lequiller and Blades, 2014).***

[82] This approach is not without limitations however, including as a result of not accounting for alterations in input-output profiles which more circular business models are likely to bring about and the use of assumed fixed-input coefficients which don't factor in price effects, including in factor markets, which can lead to 'crowding-out' effects. Combined, these can result in issues of under- or over-estimation (McCarthy, Dellink and Bibas, 2018).

methods carry relatively extensive data input requirements including price elasticity assumptions, regular and consistent bilateral trade, cross-sectional, material and historical time-series data among others (Cambridge Econometrics, 2019), making their maintenance time-consuming and required inputs application-specific. While a detailed assessment of coverage of data was not possible in relation to each of these inputs for *ex ante* assessment methods in this initial review, we set out sources identified of relevance to these methods (which overlap in many cases with those useful for retrospective tracking) while broadly outlining gaps and issues found. Of the full list of data assets identified through our search, approximately half provided information detailed and/or conforming to an industry or sectoral classification while a quarter offered a geographical breakdown in the information they captured.

Box 3. Classifications used in tracking the UK economy and the role of improved classifications in measuring and modelling the circular economy

Our review identified a range of sources capturing information on different phenomena, and a variety of classifications (i.e. nomenclature systems) in use across shortlisted data assets including when referring to similar things. Classifications were found to differ by sources across scales and value-chain stages, with some more predominant than others and several topical areas and publishers exhibiting higher levels of consistency and interoperability in classifications used. A list of key classifications can be found here.

The UK National Accounts (UKNA) describe national production, income, consumption, accumulation and wealth, and are the basis from which key national-level aggregates and indicators such as gross domestic product (GDP) are derived. The UK accounts are compiled by the UK ONS largely in accordance with the System of National Accounts (SNA), an internationally agreed standard set of recommendations introduced in the 1950s on how to compile national accounts covering agreed concepts, definitions, classifications and accounting rules. The SNA broadly separates economic actors into producing units (mainly corporations, non-profit institutions and government units) and consuming units (mainly households). On the production side and as part of the UKNA, industries are classified into branches of homogeneous institutional units producing goods and services described under a given heading of a product classification (Lequiller and Blades, 2014). The *Standard Industrial Classification* (SIC) 2007, the first version of which was introduced in 1948 and which has since been revised several times, is a hierarchical 5 digit framework used in the UKNA to classify businesses by the type of economic activity they engage in.

Companies are self-assigned to at least one (and up to four) of a condensed list of SIC codes (~730) when registering with the UK Companies House and again, but to a single code associated with their highest value-added activity (principal activity), for most statistical returns (Jacobs and O'Neill, 2003). The UK SIC (2007) is based on the 4 digit *International Standard Industrial Classification of All Economic Activities* (ISIC) developed by the UN (ONS, 2009) while mirroring the NACE Rev. 2 classification developed by Eurostat and adding a further digit of detail where deemed useful. Overall, the UK SIC (2007) consists of 21 sections, 88 divisions, 272 groups, 615 classes and 191 subclasses, with a revision to the current structure planned in 2023.

As a way of classifying industry *activities*, the SIC links to a range of additional key classifications used to track dynamics of interest in the economy. For instance, an SIC code in conjunction with information on a firm's legal and ownership status can help attribute that firm to a sector under the UK *Sectoral Classification for the National Accounts* (Prosser, 2009) in line with the different incentives they face. The *Classification of Products by Activity* (CPA) coding frame for describing *products* (goods and services) at the level of the EU maps onto and extends the SIC classification by two further digits in alignment with the UN *Central Product Classification* (CPC). Prodcom headings used in statistics on UK manufacturing production draw on up to eight-digit numerical codes, the first six of which align with the CPA and with two additional digits for further detail. For consuming units, the UN Classifications of Expenditure According to Purpose (UN, 2000), as a functional classification, is composed of the *Classification of Individual Consumption According to Purpose* (COICOP) used in the UK to categorise statistics on household final consumption expenditure (HHFCE), in addition to the UN *Classification of the Functions of Government* (COFOG) which can be used to categorise individual and collective consumption expenditure undertaken by the government.[83] The SIC classification also links to the *Standard Occupational Classification* (SOC) used to categorise occupations and employment.

Reading across to classifications of trade statistics maintained by HMRC, the 6 digit *Harmonised Commodity Description and Coding System* (HS) advised by the World Customs Organisation which, in turn, forms the basis of the 8 digit *Combined Nomenclature* (CN) used by Eurostat and links to the UN's *Standard International Trade Classification* (SITC), is consistent with nomenclature systems for describing domestic production drawn on in the UK. This enables comparison between domestic production figures for a given product and industry (ONS, 2009) and trade. Other relevant but as of yet, less widely established classifications include the *Classification of Environmental Protection Activities* and *Classification of Resource Management Activities* used in tracking the activities in the 'Environmental goods and services sector' in the UK.

Standardised classification systems and unique identifiers help structure the collection, tabulation and presentation of data while promoting statistical uniformity, interoperability and findability among other things (UNECE, 2021a). Through the use of harmonised classifications, barriers associated with matching entities, products and activities across different data sources, variables of interest, value chain stages (including those 'post-use') and levels of detail can be reduced. Furthermore, coding producers and products in line with standardised classifications facilitates access to a rich and interoperable source of data integrated into established publication cycles on a range of economic variables (Livesey, 2010) in addition to, increasingly, wider environmental parameters.

As stated by the UNECE (2020), the circular economy is a cross-cutting concept, the scope of which is not easy to delimit at present in statistical terms. Difficulties therefore arise in tracking the circular economy in the national accounts due to insufficient delineation in areas of interest. The changing structure of the economy means that statistics collected will often be out of date, under-represent newer industries and must be updated continually in line with society's needs (Bean, 2016; Lequiller and Blades, 2014). For instance, while renting of video tapes and disks (77220) is currently represented in the UK SIC, many areas of growth such as fintech as well as more detailed components of waste management are not tracked in detail. The Data City (2020) reports that a third of UK companies are classified under an SIC code beginning with 'other' and most commonly '82990 - other business support service activities not elsewhere classified', potentially distorting statistics across other codes. Jacobs and O'Neill (2003) highlight issues with the internal and comparative consistency of SIC codes in the UK and further afield. Notwithstanding some of these issues, an important step in improving the data and evidence base for tracking the UK circular economy within current data collection systems is classifying relevant activities and products so as to make them explicit in collected statistics.

Monetary data sources

Extrapolation inputs and indirect secondary effects

Table 11 sets out data assets identified through our search as relevant to industry-level extrapolation of estimates made at preceding micro- levels of assessment and for appraising indirect secondary-round effects using multipliers. The use of scaling factors need to be tempered by realistic assumptions regarding the share of an industry to which a change might be viable furthermore.

Table 11. Data assets relevant to the meso level (extrapolation and secondary effects)

Dataset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown

[83] The UN Classifications of Expenditure According to Purpose is further composed of the classification of the purposes of non-profit institutions serving households (COPNI) and classification of the outlays of producers according to purpose (COPP), though these are less widely used (Mahajan *et al.* 2018).

UK Business: Activity, Size and Location[84]	Numbers of VAT and/or PAYE registered businesses and local units at end financial year produced from a snapshot of the Inter-Departmental Business Register (IDBR).[85]	ONS	Count	UK, Region	1971-1997 (not digitally available), 1998-2002 (SIC92), 2003-2008 (SIC03), 2008-21 (SIC07); annual; 1	Enterprise/local units by: legal status, industry (down to 4-digit SIC level), employment and turnover size bands
Supply and use tables	Input, output, supply (domestic & imported), use (intermediate, final domestic, exports), GVA generation, expenditure and income.	ONS	£	UK	1997-2020, annual, 1.75	105 product/industries, 8 final uses 112 industries, 112 products
Input-output analytical tables	Industry inputs and outputs, product supply and demand, and gross value added (GVA) for the UK.	ONS	£	UK	1984-2018, annual since 2013, 3	Product x product Industry x industry[86]

Figures on business numbers captured in the publication 'UK Business: Activity, Size and Location' presents a snapshot of the Interdepartmental Business Register present down to a SIC07 class level of granularity, and by including enterprise numbers by geography, industry, legal status and employment size band, can inform rough but disaggregated scaling factors for use in estimating the wider potential relevance of changes modelled at an individual-business or value-chain level.

SUTs are an important National Accounts product for balancing and reconciling the production, income and expenditure approaches to measuring key macroeconomic aggregate indicators such as national-level GVA and GDP (ONS, 2014). The UK SUTs help describe the economy in terms of the flows of products and services between sectors and components of final demand in a given period, with the supply table more specifically showing output of product by industry and the use table showing how inputs are used in intermediate and final demand. The UK input-output analytical tables (IOATs) are derived from the SUTs and are designed to support additional analysis such as assessing the direct and indirect/supply-chain effects of a change in final demand. The IOATs are supplied in industry-by-industry and product-by-product formats by the UK ONS, with industries in the source classified using the UK SIC07 and products, CPA 2008 (ONS, 2022).

Since a 2006 review undertaken by Wiedmann *et al*. (2006) which identified a lack of timely UK data undermining robust MRIO analysis, SUTs and IOATs have been produced more regularly, with the latter published annually since 2013. As the culmination of an extensive National Accounts production process (with the SUTs drawing on at least 245 inputs[87]) and despite a progressive reduction in this time-period

[84] Estimates of business birth and death rates also based on the IDBR are captured in the ONS 'Business Demography' publication which are thought to provide a more comprehensive assessment at a national-level

[85] Covers the vast majority of UK businesses but excludes agriculture, public administration and businesses not VAT or PAYE registered

[86] Captures outputs of the whole industry which includes primary (main output) and secondary production (products produced by the industry other than their main output).

[87] https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/supplyandusetablesdatasourcescatalogue

over the last two decades, the lag associated with these data sources nevertheless and somewhat unavoidably, remains high. In addition, the resolution of products and industries that these inputs are presented in line with remains coarse (~100 industries/products for the whole economy), with limited distinction between products or facilities using primary vs. secondary raw materials in the social accounting matrix (OECD, 2021).

Wider monetary flows, stocks and economic dynamics

Table 12 sets out further data assets identified through our search which present monetary or economic aspects at a sectoral or industry level. These can be relevant to a specific value chain stage or across several. It was found that for most institutional sectors as well as within the corporation sector, regularly (quarterly and annual) updated economic figures are published as part of the National Accounts capturing a breadth of information including on: economic production; the generation, allocation and the secondary distribution of income; consumption expenditures; capital accounts; financial accounts and balance sheets (Lee, 2011).

Table 12. Data assets relevant to the meso level (monetary flows, stocks & economic dimensions)

Dataset	What does it tell us in relation to this input requirement?	Value chain stage	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
UK Manufacturers Sales by Product (Prodcom)	Captures at a four-digit SIC level variables including merchanted goods,[88] work done,[89] waste products[90] and non-production income.[91]	Inflow, Use, Outflow	ONS	£	UK	1993-2021 (1993-2007 not directly comparable to 2008 +), biannual, 0.75 (provisional), 1.5 (final)	~3,770 products (interoperable with NACE, CPA, CN), 234 industries
Non-financial business economy, UK: Sections A to S	Monetary data on turnover, employment, input costs and aGVA for UK businesses in the production, construction, distribution and	Inflow, Use, Outflow	ONS	£, count	UK	1997-2020, annual, 1.5	20 sections

[88] Value of sales of goods that have been bought in and resold without being subject to any manufacturing process.

[89] Refers to the amount charged to a customer by a business, for work done on material provided by the customer The business does not report the final product in product sales as the materials are owned by the customer, not the business.

[90] The value of sales of waste products and residues left over after manufacture.

[91] Derived from the provision of services and other non-production activities not listed in the other variables above This could include freight costs, payments for repairs, maintenance and installation of customers' plant and equipment (where not covered by an industrial services product code), amounts received for use of patents, trademarks, copyrights, royalties, technical knowledge, rent etc.

	service industries based on the Annual Business Survey.[92]						
Construction industry output data	Construction output in GB, split by private and public sector and housing, other, infrastructure and repair and maintenance.	Inflow, Use	ONS	£	GB	1997-2022, monthly 0.2	New work vs. repair & maintenance Construction type e.g. housing/infrastructure Public/private
Regional gross value added (balanced) by industry: all ITL regions	Annual estimates of balanced UK regional gross value added (GVA(B)).	Inflow, Use, Outflow	ONS	£	UK	1998-2020, annual, 1.5	ITL1, ITL2 and ITL3 regions
Remanufacturing market study	Estimate the current level of remanufacturing activity within the EU, including the UK and Ireland.	Outflow	Parker *et al.* (2015)	£, number	UK and Ireland	~2015	9 sectors; 9 regions
Gross fixed capital formation by industry and asset Gross fixed capital formation – by sector and asset	Industry, sector and asset breakdowns of gross fixed capital formation (GFCF), including business investment.	Inflow, Use	ONS	£	UK	1997-2020, annual, 1.75 1997-2021, quarterly, 0.25	83 industries across 11 asset classes 6 institutional sectors, 5 asset types
HMRC tax receipts	Summary of HM Revenue and Customs'	Inflow, Use, Outflow	HMRC	£	UK	1999-2022 (annual), 04/2008-	Receipts (40 categories),

[92] Covers only the UK Non-Financial Business Economy which accounts for approximately two thirds of the UK economy in terms of gross value added.

and National Insurance contributions	tax receipts, National Insurance contributions (NICs), and expenditure for the UK					09/2022 (monthly), 0.1	expenditure (7 categories),
National balance sheet	Sector and asset breakdowns of the estimated market value of financial and non-financial assets in the UK.	Use	ONS	£	UK	2012-2020, annual, 1	11 institutional sectors 15 non-financial asset classes, 8 financial asset/liability classes
Environmental goods and service sector	Estimates of the UK's environmental goods and services sector: output, gross value added, employment and exports.	Inflow, Use, Outflow	ONS	£, count	UK	2010-2019, annual, 2.5	17 activities Classification of environmental protection activities (CEPA) (7) Classification or resource management activities (CReMA) (9) SIC Sections (19[93])
Environmental protection expenditures	Estimates for the UK's total environmental protection expenditure as defined by SEEA.	Inflow, Use, Outflow	ONS	£	UK	1993,1997, 1999-2013 (Defra methodology) 2010-2018, annual, 2.5	Expenditure type SIC Section & Division breakdown for manufacturing External/in-house/end-of-pipe,

[93] Excluding ‘activities of households as employers; undifferentiated goods-and services-producing activities of households for own use’ and ‘activities of extraterritorial organisations and bodies’.

							OPEX/CAPEX
Environmental taxes	UK government revenue from environmental taxes (including energy, transport and pollution or resource taxes).	Inflow, Use, Outflow	ONS	£	UK	1997-2021, annual, 0.5	Revenue by: Tax type Economic activity: NACE (9), households, non-residents

At the four-digit SIC level, Prodcom captures variables including 'merchanted goods', 'work done', 'waste products' and 'non-production income', which greater circularity might be expected to be reflected in, though how and to which magnitude would need to be explored further. Nevertheless, Prodcom only covers Division 33 across SIC/CPA, meaning volume-based measures for subsequent divisions e.g. Waste collection, treatment and disposal services; and Materials recovery services are not provided.

The data asset entitled 'Non-financial business economy, UK: Sections A to S' is more comprehensive in its coverage and captures a range of useful economic variables for industries making up approximately 2/3rds of the economy to a 4 digit class-level. These include enterprise numbers, total turnover, approximate GVA, purchases, capital expenditure and disposals and stocks. The source provides data on a range of relevant activities across the value chain including those linked to use-phase extension e.g. resale and repair and at the outflow/reverse loop stage, such as waste collection, treatment and materials recovery. Below, we list examples of relevant UK SIC07[94] codes for which data is provided in the publication.[95]

- **Repair of machinery and equipment** (33.1)
  - 33110 Repair of fabricated metal products
  - 33120 Repair of machinery
  - 33130 Repair of electronic and optical equipment
  - 33140 Repair of electrical equipment
  - 33150 Repair and maintenance of ships and boats
  - 33160 Repair and maintenance of aircraft and spacecraft
  - 33170 Repair and maintenance of other transport equipment n.e.c.
  - 33190 Repair of other equipment
- **Waste collection** (38.1)
  - 38110 Collection of non-hazardous waste
  - 38120 Collection of hazardous waste
- **Waste treatment and disposal** (38.2)
  - 38210 Treatment and disposal of non-hazardous waste
  - 38220 Treatment and disposal of hazardous waste
- **Materials recovery** (38.3)

[94] The full list of SIC codes can be found here, while the condensed list supplied to Companies House for business self-selection can be found here.

[95] These align furthermore with the NACE codes used by Eurostat to track the indicator 'Private investments, jobs and gross value added related to circular economy sectors (recycling, repair and reuse') (Eurostat, 2021). Proxies used by Wrap and the Green Alliance (2015) can be found here.

    - 38310 Dismantling of wrecks[96]
    - 38320 Recovery of sorted materials
- **Remediation and other waste management services** (39)
- **Maintenance and repair of motor vehicles** (45.2)
- **Sale, maintenance and repair of motorcycles and related parts and accessories** (45.4)
- **Wholesale of waste and scrap** (46.77)
- **Retail sale of second-hand goods in stores** (47.79)
- **Renting and leasing of motor vehicles** (77.1)
    - 77110 Renting and leasing of cars and light motor vehicles
    - 77120 Renting and leasing of trucks and other heavy vehicles
- **Renting and leasing of personal and household goods** (77.2)
    - 77210 Renting and leasing of recreational and sports goods
    - 77220 Renting of video tapes and disks
    - 77291 Renting and leasing of media entertainment equipment
    - 77299 Renting and leasing of other personal and household goods
- **Renting and leasing of other machinery, equipment and tangible goods** (77.3)
    - 77310 Renting and leasing of agricultural machinery and equipment
    - 77320 Renting and leasing of construction and civil engineering machinery and equipment
    - 77330 Renting and leasing of office machinery and equipment (including computers)
    - 77341 Renting and leasing of passenger water transport equipment
    - 77342 Renting and leasing of freight water transport equipment
    - 77351 Renting and leasing of air passenger transport equipment
    - 77352 Renting and leasing of freight air transport equipment
    - 77390 Renting and leasing of other machinery, equipment and tangible goods n.e.c.
- **Repair of computers and communication equipment** (95.1)
    - 95110 Repair of computers and peripheral equipment
    - 95120 Repair of communication equipment
- **Repair of personal household goods** (95.2)
    - 95210 Repair of consumer electronics
    - 95220 Repair of household appliances and home and garden equipment
    - 95230 Repair of footwear and leather goods
    - 95240 Repair of furniture and home furnishings
    - 95250 Repair of watches, clocks and jewellery
    - 95290 Repair of personal and household goods n.e.c.

Other codes captured in the publication give insight into areas where declines might be expected or sought under a structural shift towards a more circular economy. Of the activities making up reverse loops, repair appears particularly well detailed in the SIC07 classification and, in turn, this data source.[97] There is a lack of detail for many reverse loop activities which would still involve some level of economic production and conceptually meet the survey boundaries. These include remanufacturing (Oakdene Hollins, 2022) and biorefining (Wrap, 2022). These gaps impact not only monetary figures, but also job statistics. Further exploration of how businesses who conduct ‘reverse-loop’ activities that are not separately/explicitly captured in the UK SIC07 go about self-selecting from currently available codes would be valuable. For instance, searching the Companies House register for active companies with the

[96] Including automobiles, ships, computers, televisions and other equipment.
[97] Repair has been present in every classification since the first UK SIC was introduced in 1948.

term ‘refurbish’ or ‘refurbishment’ in their business names brought up approximately 700 companies. Many of the companies reviewed self-identify by SIC codes making them largely indistinguishable from non-refurbishment activities (e.g. 41202, 43341, 43390, 43999, 43440).

Gross value added (GVA) measures the increase in the value of the economy due to the production of goods and services calculated as the difference between the value of goods and services sold and intermediate expenses incurred to produce these. Potential effects on net-GVA are frequently used as a basis for appraising more circular alternatives (e.g. Wrap, 2016). Regional (and national) GVA[98] figures are estimated for the economy as a whole by the ONS through balancing GVA estimates made using income[99] (drawing partially on data captured in the ABS)[100] and production[101] approaches apportioned to regions using best available data (ONS, 2019b). Varying levels of industry detail are supplied depending on geographical scale (112 industries for ITL1, 72 industries for ITL2 and 48 industries for ITL3) (ONS, 2019b). The regional breakdown offered helps give insight into geographical clustering and distributional effects, however higher uncertainty can be expected with the most spatially disaggregated figures. Nevertheless, the level of detail in this publication makes it difficult to track activities linked to post-use reverse loops as these are embedded within wider industries and not separated out, though sources such as the ABS can be used in conjunction to do so.

GVA tracks gross monetary flows (including gross fixed capital formation) without accounting for monetary depreciation in underlying capital stocks. Since 2012, the UK National Accounts have included estimates of the market value of financial and non-financial assets to help track national wealth - defined in terms of the net market value of capital assets (including dwellings, machinery and equipment). A perpetual inventory method (PIM) is drawn on by the ONS to track the national balance sheet with this split by industry, sector and asset-type. For non-financial assets, the PIM method involves starting with a benchmark asset value and accumulating asset purchases from gross fixed capital formation data over their estimated lifetime (based on ad-hoc research e.g., asset lives study) alongside an assumed capital retirement distribution (linear in the UK) to estimate *gross* capital stocks. From this, a depreciation function is used to estimate the *net* capital stock (Dey-Chowdhury, 2009). Although this function has historically been assumed as linear, since 2019 it has taken the form of a wider range of nonlinear patterns in published statistics (ONS, 2019c). Statistics on gross fixed capital formation[102] which inform these asset estimates are published separately by the ONS.

Several additional data sources relevant to the meso level were identified which provide more granular insights into specific industries and sectors such as for the ‘Environmental goods and services sector’ (EGSS) tracked in terms of output, GVA, employment and exports by the ONS at a UK-level (residency basis) as part of the Environmental Accounts (ONS, 2021). The publication monitors this defined sector in terms of: 17 activity categories; by SIC (n=19); and based on two specifically developed multi-purpose functional classifications - CEPA 2000 (n=9) and CReMA 2008 (n=7) used for categorising activities, products and transactions whose primary purpose is environmental protection or the management of

[98] A measure of ‘the increase in the value of the economy due to the production of goods and services’. The difference between turnover and costs of intermediate inputs.

[99] Largely the sum of compensation of employees, rental income and gross trading profits.

[100] The Annual Business Survey’s measure of approximate gross value added is refined with scope, coverage and value adjustments to produce national-level GVA statistics (ONS, 2020).

[101] Sum of all output (market and non-market, with the latter measured in terms of production costs) less intermediate consumption.

[102] Gross investments into fixed assets intended for use in the production of other goods and services for a period of more than a year.

natural resources.[103] Of most direct relevance to the circular economy, the source captures data on 'recycling'[104] and 'waste'[105] under the activity classification, 'waste management' under the CEPA classification and 'water supply; sewerage, waste management and remediation activities' under the SIC classification breakdowns.

Several further sources identified in our search tracked other dynamics of relevance at the meso-level by being areas in which structural change might have wider impacts. These include for the economic costs of waste management or tax/exchequer receipts. From the Environmental Accounts, the data source 'Environmental protection expenditures' captures information regarding in-house and external operating expenditures[106] and end-of-pipe[107] and integrated[108] CAPEX across the divisions making up sections B through E. As well as being broken down by tax, the source 'Environmental taxes' presents total payments (and then with an additional year's lag, split by energy, transport and pollution and resource taxes) across 9 broad NACE categories and three further categories of 'households', 'non-residents' and 'unallocated'.

Together, these monetary data were viewed as constituting a quite systematic, comprehensive (to activities within the domestic economic territory) and internally consistent basis of financial variables particularly for characterising the BAU case. Nevertheless, poor levels of detail in some areas in underpinning classifications mean key industries particularly relevant to the circular economy were found to be under-represented in many of the reviewed publications. Other sources identified of potential relevance include: HMRC data on VAT receipts including by sector (n=22) and sub-sector (n=89).

Material flows and stocks

The SEEA-CF is a '*multipurpose conceptual [accounting] framework for describing the interaction between the economy and the environment, and the stocks and changes in stocks of environmental assets*' (pg. 11). It applies the accounting concepts, structures, rules and principles of the SNA to environmental information. Prior to the introduction of the System of Environmental-Economic Accounts Central Framework (SEEA-CF) in 1993, the SNA (which governs a great deal of UK National Accounts development), provided little guidance on how to reflect within national accounts damages to the environment from economic activity or the value the environment provides to the economy (LaNotte and

[103] The source draws on data from: the SUTs for GVA; the ABS for its greater disaggregation which allows SUT estimates for GVA to be apportioned to relevant activities assumed share of those activities making up an industry; the IDBR; the Environmental Protection Expenditure (EPE) Survey; and Low Carbon and Renewable Energy Economy (LCREE) Survey (which asks businesses if they undertake any activity in seventeen activity areas included in the publication).

[104] "This activity includes the salvage of wrecks (automobiles, ships, computers, televisions and other equipment), and the processing of metal and non-metal waste and scrap and other articles into secondary raw materials. It also includes the separating and sorting of materials from waste streams and mixed recoverable materials into distinct categories." (ONS EGSS Methodology Annex)

[105] "These activities relate to the collection, treatment and disposal of various forms of waste, such as solid or non-solid industrial or household waste, as well as contaminated sites. The output of the waste or sewage treatment process can either be disposed of or become an input into other production processes." (ONS EGSS Methodology Annex)

[106] Covering waste water management, protection of ambient air and climate, solid waste management, the protection of soil or groundwater, noise abatement, protection of biodiversity or protection against radiation

[107] "Refers to capital expenditure for methods, technologies, processes or equipment designed to collect, remove pollution and pollutants after their creation" (ONS, 2021)

[108] "Refers to investment in methods, technologies and equipment that are integrated within the businesses' overall activity" (ONS, 2021)

Rhodes, 2020; O'Connor, Steurer and Tamborra, 2000). More specifically, the SEEA-CF has sought to provide guidance to:

1. **Correct SNA aggregate measures** such as GDP or GVA for natural resource depletion and deterioration in environmental functions as well as related defensive expenditures[109]; and
2. **Expand** the national accounts though satellite 'environmental accounts', including:
    a. **Physical flow accounts** – showing how the environment contributes to the economy via physical flows and releases from the economy back into the environment as wastes and effluents;
    b. **Asset accounts** - measuring the stock of environmental assets in physical and monetary terms. For instance, timber stock accounts showing opening and closing balances in a given period or estimates of the monetary value of subsurface mineral assets[110]; and
    c. **Environmental-activity accounts** - measuring how society responds to environmental issues via, for instance, taxation, or resource management expenditures otherwise encompassed in economic accounts but not separately measured.

Through being compiled in line with the SEEA-CF, the UK Environmental Accounts are therefore broadly consistent with components of the National Accounts describing the economy. When also (dis)aggregated using consistent and similarly detailed classifications, this makes it possible to more readily link statistics on, for instance, output and value added by institutional classification code (e.g. SIC) to environmental aspects such as material inputs or environmental pressures (Hoekstra, 2020).[111]

A disaggregation by industry was found to be available for many, but not all, of the data assets making up the Environmental Accounts at this time. Specific to material flows, the UK Material Flow Accounts (MFA) seek to provide an aggregate overview, in mass, of apparent material flows at the interface between the environment and economy. These figures are estimated based on the Economy-Wide Material Flow Accounting (EW-MFA) framework developed by Eurostat since subsumed within the SEEA physical flow accounts for materials. Beyond a split between domestic extraction, imports and exports on one hand and types of material flows on the other, this publication is not broken down by contributing institutional units (whether for industries or sectors) nor does it offer meso-level insights of flows between units either. For this reason, the MFA are only discussed further under the macro/national-level section.

Aggregated physical sales volume data captured as part of the Prodcom publication might conceivably give a basis to estimate SIC Division or Section level material flows at point of sale. Suppression in published data can impede this in many cases, while the accuracy of the data is thought in some cases to also be poor. Varying expressions of physical units in this source poses a potential, though likely not insurmountable, barrier to doing so furthermore. In addition, what this does not illustrate is material inputs to production units and rather only outputs. **Further consideration of the potential role of HMRC published trade data in supporting insights into material inflows to producing units (e.g. where not finished goods) may be valuable.**

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[109] The 2025 SNA working group on 'Wellbeing and Sustainability' have re-emphasised the need for the development of adjusted output measures attributable to economic units. https://unstats.un.org/unsd/nationalaccount/SNAUpdate/WSTT.asp

[110] To consider systemic changes in ecosystem condition, the SEEA-CF was added to by the SEEA-Experimental Ecosystem Accounts (SEEA-EEA) in 2013. The SEEA-EEA provides a spatially explicit approach to quantifying change in ecosystems through Geographical Information Systems (GIS)-based mapping of ecosystem extent and condition.

[111] An example of useful paired economic-environmental analysis which can be derived includes measures of physical-monetary efficiency such as resource productivity or waste intensity.

At the time of writing, the consumption-based material footprint tracking raw material consumption[112] (RMC) and published at a UK level is currently split by material type and source country/region only, contrasting with the equivalent figures at the level of England for which the consumption-based material footprint is additionally broken down by final use sectors (including using COICOP for disaggregating household expenditure) in addition to SIC product group. By seeking to capture full upstream material inputs along supply chains, these figures can be associated with potentially high levels of uncertainty but get closer to a full picture of the material requirements associated with domestic final demand. The consumption-based accounts do not appear to make explicit the material requirements of intermediate consumption, making them potentially less informative from a production-standpoint.

Regarding the use phase of meso-level value-chains, no source of data on the stock of built assets expressed in physical terms and disaggregated by industry e.g. inventories, or sector was identified by our search. While the consumption-based material footprint published at an England level (at least for the 2021 release) provides a measure of the footprint associated with gross fixed capital formation as a component of final demand, this may be less applicable to estimating the apparent stock as a materials bank. **Further work to consider how physical stocks could be attributed to some industries based on product-level data outlined under prior headings e.g. for buildings or vehicles, could be valuable.**

At the outflow stage, institutional-level household and wider local-authority collected waste statistics are thought to be the most accurate areas of waste generation figures at present. The ‘UK Statistics on Waste’ published by Defra was also found to include biennial estimates of waste generation by 17 NACE codes as part of the ‘Waste Stat Return’, though the robustness of this attribution (particularly within the manufacturing sector) was uncertain at this time. Other waste generation statistics included in this publication such as for construction and demolition (C&D), commercial and industrial and ‘other’ categories can be mapped to equivalent SIC codes to produce, for instance, economic-physical waste intensity measures.

Outside of households and construction and demolition where recycling and recovery rates are presented, the most detailed waste treatment data source identified through our search, the ‘Waste Data Interrogator’, while a rich dataset, does not attribute waste treated to a generating source at present, making it difficult to follow in current data how waste generated by institutional units is treated. The now-consulted-on Defra ‘waste tracking system’ is expected to yield improvements in the ability to trace waste by source and treatment route, with the potential for this to improve meso-level material flow insights. Table 13 summarises meso-level sources capturing material flows identified through our search.

Table 13. Data assets relevant to the meso level (material flows and stocks)

Dataset	What does it tell us in relation to this input requirement?	Value chain stage	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag	Extra-geographical breakdown

[112] Wiedmann *et al.* (2015) [4] define RMC as the *“global allocation of used raw material extraction to the final demand of an economy… which does not record the actual physical movement of materials within and among countries but, instead, enumerates the link between the beginning of a production chain (where raw materials are extracted from the natural environment) and its end (where a product or service is consumed)*” (p. 6271).

						(year)	
England Consumption-based material footprint	The allocation of global primary used raw material extraction to final domestic demand for goods and services by residents.	Inflow	Defra	Metric tonne	England	2001-2019, annual, 2.5	7 end use/final demand categories 33 COICOP categories 112 SIC product groups
UK statistics on waste	Figures compiled on the generation of UK waste by NACE code and categories of waste e.g. construction waste and C&I waste which can be mapped to SIC.	Outflow	Defra	Metric tonne, rate, count	UK, England	2010-2021, annual/biennial, varies	Waste generation attributed to NACE (17) Industry-section generation estimates

Impact data

Several identified sources of data capturing environmental pressures with an institutional-level breakdown were identified. As part of regular publications of the UK Environmental Accounts, environmental data presented in line with an industry classification cover the following physical flows and environmentally-significant dynamics: atmospheric emissions including for each of the 7 greenhouse gases falling under the Kyoto Agreement,[113] acid rain precursors,[114] heavy metal[115] and 'other pollutants'[116] all by UK SIC07 group (n=~130); in addition to energy use from renewable and waste sources, fossil fuels and total by UK SIC07 sections (n=~21).

Outside of the Environmental Accounts, BEIS tracks atmospheric greenhouse gas emissions by SIC on a territorial basis, deviating slightly from those published by the ONS by not being accounted for on a residency basis as well as due to relatively small differences in scope such as treatment of international aviation emissions. One key issue across both sources and specific to the waste management sector is that emissions savings through activities are not reflected. The UK Pollution Release and Transfer Register (PRTR)[117] collects point-source data on emissions releases, emissions transfers and waste transfers above a set threshold from industrial or business facilities required to report to regulators, presenting this by substance, area, river basin, activity and economic sector (NACE 1-99).

[113] Carbon dioxide, methane, nitrous oxide, hydro-fluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride.
[114] Sulphur dioxide, nitrogen oxide, ammonia.
[115] Arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, vanadium and zinc.
[116] PM10, PM2.5, carbon monoxide, non-methane volatile organic compound, Benzene and 1,3-Butadiene.
[117] "A national or regional environmental inventory of potentially hazardous chemical substances or pollutants released to air, water and soil and transferred off-site for treatment or disposal". The 2003 Kiev Protocol on PRTRs requires parties to the agreement to make this information publicly available.

The 'carbon footprint' refers to the allocation of global greenhouse gas emissions to final demand for goods and services by England residents. In addition to direct emissions, the measure takes account of the emissions arising along the supply chain for imported products while excluding domestic emissions associated with exports. The carbon footprint estimates for the UK and England produced by the University of Leeds on behalf of Defra while using the same UK MRIO drawn on to construct the national material footprint estimates, offers the same sectoral and household product expenditure breakdowns in estimating emissions arising across the upstream supply chain for products making up final demand. This methodological alignment is useful in developing intensity measures between different footprints. Where this detail is variously available e.g. it was found to be published at an England level but not for the UK, this could be made more consistent by data providers going forward. The carbon footprint is the only source identified providing an upstream-perspective for environmental impacts at a meso level at this time.

Table 14. Data assets relevant to the meso level (physical impacts)

Dataset	What does it tell us in relation to this input requirement?	Value chain stage	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
Atmospheric emissions: greenhouse gases by industry and gas Atmospheric emissions: acid rain precursors by industry and gas Atmospheric emissions: heavy metal pollutants by industry Atmospheric emissions: other pollutants by industry and gas	Atmospheric emissions for a range of gases and pollutants calculated on a residency basis.	Inflow, Outflow	ONS	Tonnes, Tonnes CO2e	UK	1990-2020/1, annual, 1/2	Gas, Industry
UK greenhous	Presents estimates of UK territorial	Inflow, Use,	BEIS	Metric tonne	UK	1990-2021 (1990-2020	SIC

e gas emissions	greenhouse gas emissions by SIC code.	Outflow				final figures), annual, 2	
Pollution Release and Transfer Register Data	Point-source emissions above certain thresholds set for different effluents.	Inflow, Outflow	Defra	Tonnes CO2e, Tonnes	UK	2007-2020, annual, 1	Economic sector (NACE, 3 hierarchical levels)
Pollution Inventory	Collates information on annual mass releases of specified substances to air controlled waters and sewers as well as quantities of waste transferred off site from large industrial sites regulated by the Agency. Includes point-source and non-point-source emissions from installations.	Inflow, Outflow	EA	Tonnes, Tonnes CO2e	England	2013-2021, annual, 1	Operator name & locational information substance/waste transfer/radioactive waste Regulated industry sector/sub-sector
UK and England's carbon footprint	A measure of the global emissions attributable to final domestic demand for goods and services in the UK.	Inflow, Use,, Outflow	Defra	Metric tonne	UK/England	1995-2019, Annual, 3	7 end use/final demand categories 33 COICOP categories SIC code

Summary

From our review of publicly accessible data capturing information relevant to the at the meso-level, a variable picture of availability in relation to the input requirements of the observatory analytical framework was evident. Some suitable sources were identified that could enable micro firm-level estimates at preceding levels of assessment to be scaled to the meso-level and for estimating indirect impacts. In addition, a comprehensive range of sources capturing many variables of interest in monetary/economic terms across industries and sectors were found.

While the SNA and SEEA do not contain accounts specific to the circular economy, data collected in accordance with these can help monitor and model dynamics of relevance. For instance, the industrial classification that economic data is collected in line with, can be sufficiently disaggregated to collect information on the economic output of, and final demand for, sectors related to the sale of second-hand goods, repair, renting and leasing. In the UK, data on enterprise numbers and employment are collected using the same disaggregation, helping track dynamics across these, including with sub-national breakdown. Nevertheless, missing detail in the classifications used to compile these figures means that many reverse-loop activities such as remanufacturing are effectively indistinguishable from other production activities in the economy and only an incomplete picture of CE activities can therefore be found at this time in public statistics, with irregular market studies often relied upon to offer insight into these. Furthermore, the responsiveness of some of the variables within these datasets to CE-related changes may be limited in practice given current measurement methodologies. For instance, while current calculations of the national balance sheet utilise an internationally preferred PIM modelling method (OECD, 2009), the irregularly updated asset lifetime assumptions in this model (vs. those survey based) are unlikely to be particularly responsive to lifetime extension of capital assets through CE-strategies.

In relation to the level of data on monetary flows across industries and institutional sectors, we are lacking the equivalent in material flows and impacts for the most part. Our current understanding of material flows resulting from activities in the UK economy and its constituent geographies at the meso-level is limited in relation to many other matter flows. Gaps in data include material inputs by industry SIC code (whether on an apparent or footprint basis). Some useful data was found in trade statistics and Prodcom (for material outflows of producing units) as well as specific industrial areas e.g. agriculture, forestry and construction which could be mapped to industry classifications. With no physical input-output tables currently available in the UK, an understanding of material flows between producing units remains somewhat of a black box (Altimiras-Martin, 2014). While the consumption-based material footprint offers data on RMC by institutional sector/end use with a full value chain perspective, the relatively high uncertainty and absence of linkages to producing units reduces the policy and business usefulness of this source and arguably may implicitly place excessive responsibility on consuming units. Though some waste generation data was found to be presented in line with an economic classification, this is relatively coarse for industries in the production and services sectors and published on a biennial basis with a fairly significant lag (t-3 years). While data on waste treatment and relevant rates was found for some institutional and industry sectors, gaps for many sectors existed and an absence in the most established statistical publications mapping waste treatment data to industry sources. Across value-chain stages at the meso-level, some sectoral attributions from resource extraction to waste generation, were found to be more robust and detailed than for other areas.

A range of impact-related data expressed at the level of industries and sectors was identified through our search, including in the form of atmospheric emissions and point- and nonpoint source releases to water and land. As under the DPSIR framework, these broadly constitute pressures and few sources were identified making a final link to impacts on society. For instance and notwithstanding the development of adjusted aggregate monetary indicators in the UN Central Framework and by multilateral organisations such as the World Bank in the form of the ‘adjusted net savings’ measure (Pearce and Atkinson, 1993), no data adjusting UK meso-level monetary variables for physical impacts such as depletion in natural capital were identified. Though savings-based indicators such as the ‘adjusted net savings’ i.e. ‘Genuine savings’ offer a means of wealth accounting at a national-level, further examination of which adjusted monetary measures are most suitable to a meso-level may be valuable. Recently, the 2025 SNA working group on ‘Wellbeing and Sustainability’ has re-emphasised the need for the development of adjusted output measures attributable to economic units.

2.5 National layer

Example of stakeholder questions relating to layer

1. *What would the implications be for the environment, economy and society as a whole from increasing the circular treatment of materials?*
2. *Do we have a national-level picture of the size of the circular economy in economic terms, including associated jobs? How is that best measured?*
3. *How circular is the UK economy as a whole at present and how are we performing in relation to other countries?*

The fourth and final layer of the observatory analytical framework requires assessment at the national level. *Ex ante, this involves* against-baseline appraisal of the overall potential outcomes and impacts for the economy, society and environment/environmental pressures of more circular configurations of goods and services net of potential secondary economy-wide 'reshuffling' effects. Methods directly relevant to forward-looking appraisal at this level overlap with those relevant to the meso-level and therefore include EE-MRIO and macroeconometric modelling which, in-turn, draw on data inputs such as SUTs, IOATs and environmental accounts data. Furthermore, by incorporating outputs of assessment undertaken at micro levels of the analytical framework, the full range of methods set out in this document are indirectly relevant.

Ex post assessment at the national level involves tracking the performance of the UK to characterise and then compare on the basis of consistent criteria, the historical and counterfactual baseline state with one in which transformation levers have been applied. A range of innovative KPIs have been proposed and introduced to track national circular performance, though many existing indicators used for monitoring societal progress and impact remain as relevant now as they have to date if an indicator framework is to attend to the interests of all major stakeholders. A statistical basis for deriving macro-level KPIs across both those innovative and more established broadly needs to comprise of data on value, volume and impact dimensions across value-chain stages at a national level, within which components potentially specific to the CE are represented.

Of the data assets identified through our review, the majority could be taken as providing a macro-level picture of their subject of focus (whether for the UK or England) or one that was at least reasonably close. The reason for this qualifier is that while in some cases a census-based collection approach or one based on extrapolating a sample to give a national-level picture was used, in other cases the specific mechanisms by which data were generated: 1) allowed for reporting exemptions such as the *de minimis* threshold in place for some EPR regulations; 2) unavoidably rendered published figures a function of enforcement activities such as data on illegal waste sites (NAO, 2022); or 3) were impacted by issues of illegal non-reporting not otherwise sought to be accounted for via any form of adjustment. In some areas, attempts were found to be made to tackle these gaps and provide a national-level picture e.g. Valpak's material flow reports which seek to estimate non-reported flows of EPR-regulated products.

A quarter of those data assets providing a (close to) macro-level picture also presented data with a geographical breakdown (such as for a region or local authority), while roughly half gave an institutional-level of detail such as for an industry or sector. This highlights the overlap between data sources relevant to the macro-level of assessment and those preceding, but also that data assets capturing macro-level dynamics are not always aggregates of industry, sector, geographical or product-detailed statistics. Whether capturing data on value or volume flows or impacts, half provided information relevant to 'inflow' value-chain phases, two-thirds covered 'outflow' value-chain phases and a quarter captured information on 'reverse flows' with only a small number of sources related to the use phase.

Monetary flows and stocks

Table 15 sets out data sources identified through our search as relevant to modelling and monitoring the UK (circular) economy at the national level expressed in a monetary unit. For brevity and due to the overlap between sources relevant to assessment at the national-level and those preceding, we only present within the tables in this section any sources not otherwise already introduced in the working paper, but examine the coverage of all relevant sources in the accompanying text.

Table 15. Data assets relevant to the national level (monetary/monetized flows and stocks and economic dimensions)

Dataset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
Quarterly country and regional GDP	Measures the value of goods and services produced in the UK used to gauge the size of and growth in the economy.	ONS	£	England and Wales 9 English regions	1955-2021, monthly/quarterly, 0.25	More detail on components of GDP at UK-level in linked datasets e.g. GDP quarterly national accounts time series
Financial statistics for public sector	Captures central government receipts, expenditure, borrowing, deficit and debt data.	ONS	£	-	2015-2022, monthly, 0.5	Receipt, expenditure, Net cash requirement, borrowing, deficit and debt Sub-sector: central and local government & public corporations

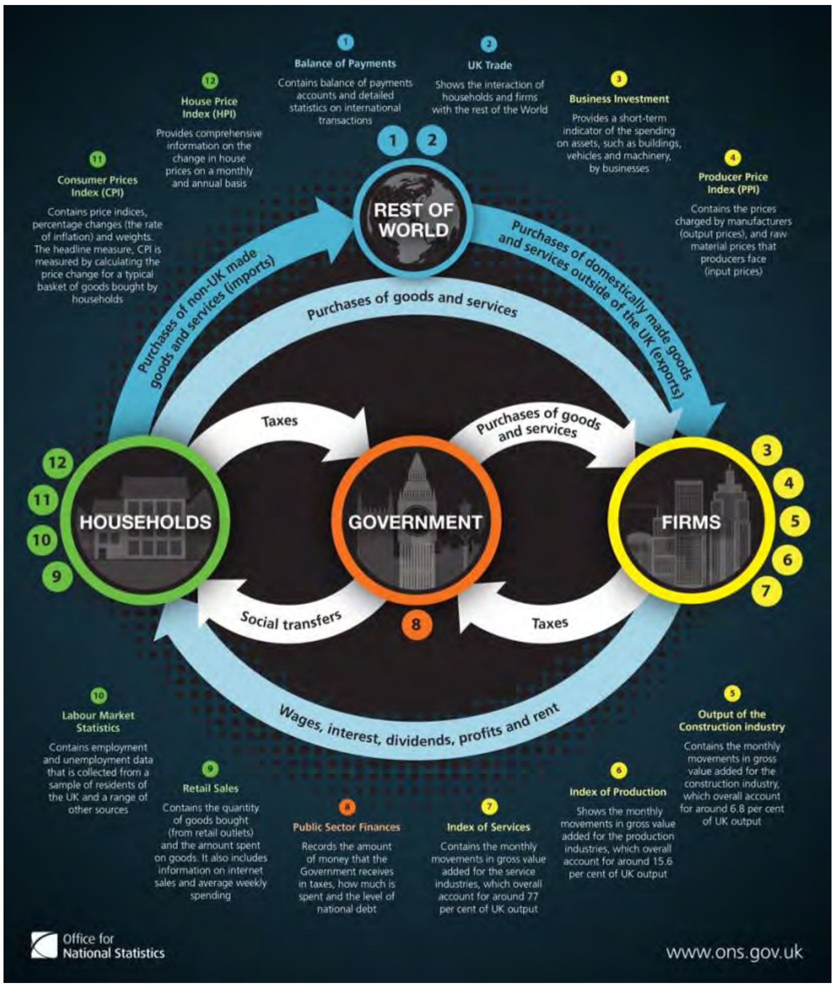
The UK National Accounts and related statistics capture a breadth of data on national-level variables including output, consumption and savings, capital formation, trade, income, tax, subsidies and financial transactions between firms, and in turn, households (Lee, 2011). These data are captured across a range of sources and collated in the UK Blue and Pink Books to give an overall picture of economic activity.

GDP[118] is the headline macroeconomic aggregate of the SNA, the most widely used metric for tracking national economic development at present and the maintenance/growth in which remains an implicit, if not explicit, goal of many governments. Therefore, a comparison of environmental benefits to GDP effects

[118] GDP '*combines into a single figure…[the monetary value of] the [market] output…carried out by all the firms, non-profit institutions, government bodies and households in a territory during a given period, provided that the production takes place within the country's economic territory*' (OECD, 2014, p.15)

underpin many *ex ante* assessments of circular economy strategies (Cambridge Econometrics, 2014; McCarthy, Dellink and Bibas, 2018; Bibas, Chateau and Lanszi, 2021). The emphasis on GDP is not without critique however, including due to omissions of value associated with non-marketed production, potential mismeasurement of nominal GDP from new services, omission of welfare-generating activities such as the sales of second-hand goods and an insensitivity to capital depreciation (Stiglitz, Sen and Fitoussi, 2009; Dynan and Sheiner, 2018; Dasgupta *et al.* 2021).[119]

Figure 6. Datasets published by the UK ONS capturing sectoral transactions and transfers at an aggregate level (ONS, 2014)



While the UK National Accounts apparatus has grown to enable the tracking of multiple components of economic activities at the national level, the extent to which a comprehensive picture of the overall size of

[119] For those proponents of moving 'beyond GDP', some commentators recommend more marginal shifts in focus e.g. the use of Gross National Income (GNI) or Gross National Disposable Income (GNDI) as an improved indicator of the monetary resources (flows) available to those who live in a country-including for welfare-generating consumption and saving activities. Alongside, there has also been a push to develop more significantly different measures of societal development altogether, including within the SNA system e.g. adjusted savings and output measures, and others without e.g. the Human Development Index or the non-composite 'Doughnut economics'. There has also been a growing interest in shifting the focus of monitoring towards balance sheets or capital assets rather than flow measures.

the CE can be painted by these, as is, remains a question. It is worth noting that the idea of estimating the size of the CE such as in terms of output or jobs and as separate from the wider economy is not without contention. On one hand and based on a collection of SIC codes, estimates have been put forward for the size of the UK CE (and change within it) in terms of jobs by Wrap and Green Alliance (2015; 2016; 2021), who highlight gaps in monetary data for biorefining and remanufacturing undermining a comprehensive picture being derived.[120] In addition, Defra in its collection of statistics the "Waste Digest", tracks several SIC codes taken to represent the 'waste prevention sector' in terms of GVA. On the other hand, the Welsh 'Beyond Recycling' indicator proposal, states the "aim [being for the] economy as a whole to become circular, not one which has a desired percentage of circular economy jobs". See the 2021 ONS article 'The challenges of defining a "green job" for an overview of this subject.

Unavoidably, estimates of national-level variables for the CE such as output, value added or jobs calculated as an aggregate of meso-level sectoral activities or products will be limited in their comprehensiveness by gaps in the current SIC system. Other sources capturing relevant information include economic forecasts produced by the Office for Budgetary Responsibility prepared for forecasting public finances and components of the economy. These act as *de facto* standard growth-rate assumptions in public cost-benefit analysis.

Material flows and stocks

Table 16 sets out sources capturing information on material flows (including residuals) across value chain stages at the national-level and not otherwise already presented in this working paper. We discuss wider data coverage in relation to national-level material flows in the associated commentary.

Table 16. Data assets relevant to the national level (material flows and stocks)

Dataset	What does it tell us in relation to this input requirement?	Value chain	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
Material flow accounts	Overview of direct material inputs into the UK economy from the domestic environment and imports, in addition to outflows from the economy in the forms of exported materials (raw, semi-finished and finished) and waste.	Inflow, outflow	ONS	Metric tonne	UK	1990-2020, annual, 1.5	13 materials (DE), further disaggregation in imports & exports

[120] A wider perspective attributing indirect jobs to circular economy activities based on a method developed with UNEP has underpinned Circle Economy's assessment for Northern Ireland (Circle Economy, 2022).

Consumption-based material footprint	**Consume:** The allocation of global primary used raw material extraction to final domestic demand for goods and services by domestic residents.	Inflow	ONS	Metric tonne	UK 15 source county & world regions	1990-2019 (UK)	4 material categories

The most widely established framework for measuring material flows at a national level is the Economy-Wide Material Flow Accounting (EW-MFA) system (Eurostat, 2018).[121] The EW-MFA system provides guidance on constructing an overview, in mass, of material inputs into an economy from the environment, net addition to stocks and outflows from the economy (both to the environment and via exports). EW-MFA is broadly consistent with the accounting principles of the SNA, though with some potential discrepancies in practice. Furthermore, in contrast to GDP, which captures final domestic demand and revenues from net-exports in monetary terms, measures of national material inflows on an apparent basis track domestic extraction and physical-net imports, reflecting that trade in materials and money move in opposite directions (Eisenberger *et al.* 2016). Several headline variables from the EW-MFA are reported on by the ONS at present, including domestic extraction (DE), domestic material consumption[122] (DMC) and direct material input (DMI). EW-MFA variables relating to the use (e.g. net additions to stocks) and downstream phase (e.g. domestic processed output through releases to the environment) are not.

Including on behalf of the UK in the past, figures derived from the EW-MFA system alongside those on waste treatment have been used by Eurostat to produce the macro-level indicator 'circular material use rate' (CMUR) which tracks the proportion of waste recovered (CMU) against material demands of the economy based on the following function: = (CMU/(CMU+DMC))*100, where CMU[123] refers to the circular use of materials (Eurostat, 2018).[124] Issues with the use of CMU as specified include that by being grounded in waste statistics, only the contribution of the waste management system to the circular economy is approximated while excluding any material reverse flows which do not enter the waste management system such as secondary raw materials traded between firms (Eurostat, 2018). In addition, waste statistics generally track the input of waste into a recovery operation rather than the amount of materials resulting from them. Issues with DMC which apply to the EW-MFA system more widely, include that by tracking material flows on an apparent basis, traded components are measured in terms of the mass of materials and products crossing the border, contrasting with the treatment of domestic extraction which is measured in terms of raw materials extracted. Where goods crossing borders are raw materials this doesn't immediately pose an issue, however where they are finished or semi-finished products, there is a risk of the systematic underestimation of the quantity of raw material extraction required to satisfy demand for import-intensive countries such as the UK. Consumption-based material flow accounting methodologies go some way to tackling this issue of 'asymmetry' (see Box 4).

Box 4. Measuring national material consumption

[121] Which underpins the SNA SEEA Material Flow Accounts.

[122] Calculated by summing domestic extraction and the weight of imported raw materials, semi-finished and manufactured products, while excluding the weight of exported raw materials, semi-finished and manufactured products.

[123] Approximated by waste recycled in domestic recovery plants minus imported waste destined for recovery plus exported waste destined for recovery abroad.

[124] Guidance is also available to calculate this rate by the four broad material types captured in the EW-MFA based on assumed material composition shares for each EWC-STAT group used in classifying the waste statistics.

At a global level or in a closed economy, [the sum of] domestic used extraction is equivalent to consumption-based material flow indicators such as domestic material consumption or raw material consumption, as well as input-based indicators given all trade flows net out.[125] While valuation of environmental flows (including the MFA) and assets as part of the UK Environmental Accounts is done on a domestic (residency in some cases) basis, in recent years policy makers have become increasingly aware of the significance of indirect resource consumption embodied in internationally traded products. To more accurately capture the environmental implications of trade amid increasingly globalised value chains, consumption-based accounting has sought to complement more traditional production-based accounting (Peters and Hertwich, 2008) such as EW-MFA (Wiedmann *et al.* 2008; Minx et al, 2009; Barrett, Owen and Sakai, 2011).

Broadly, there are three approaches to calculating indirect material flows (Lutter and Giljum, 2014; Tukker, Giljum and Wood, 2018). The first is a bottom-up approach drawing on supply-chain-wide coefficients derived from LCAs, the use of which help avoid aggregation errors but which are difficult to apply to all materials and products making up final demand while having a higher likelihood of truncation errors and inconsistencies including in the years from which data are sourced (Owen, Giesekam and Barrett, 2017). The second is a top-down approach using economic data captured in input-output tables to reallocate global environmental pressures to final demand using an Environmentally-Extended Multiregional Input-Output model (EE-MRIO).[126][127] This approach helps calculate the footprints for all products and sectors in an economy in a systematic way through avoiding truncation errors and better accounting for reimports. The third are various hybrid forms of these two (Tukker, Giljum and Wood, 2018).

Until recently, there were two approaches to measuring the UK's raw material consumption (RMC) published by the UK government. The first and based on a hybrid method developed by Eurostat worked by applying 'raw material equivalents' (RME) to monetary import and export data using coefficients. While these coefficients continue to be published, since EU Exit, they no longer account for UK-level data and as a result, estimates based on this approach have not been published in and for the UK since 2020 (for 2017). The second is produced by the University of Leeds on behalf of the government using an EE-MRIO approach which has emerged as the leading estimate of national-level RMC.[128] Derived figures are estimated by reallocating domestic extraction (as calculated through the SEEA and EW-MFA accounting system) by country and world region, to final demand in the UK in a given year using a MRIO database underpinned by the SUTs and IOATs produced by the UK Office for National Statistics (ONS) and input-output tables compiled within the EXIOBASE MRIO database for trade data (sourced from US COMTRADE) alongside separate sources for material extensions. The measure incorporates policy-relevant breakdowns such by final demand sector, SIC product group and components of household expenditure under the COICOP classification (as in the England-level release). These estimates are also consistent with figures published on the UK's carbon footprint.

EE-MRIO methodologies are data intensive, requiring regular information on material extraction and production

[125] The indicators total material consumption and total material requirement (TMR) expands the system accounting boundary by including unused flows. TMR measure is the most comprehensive out of material flow measures presented and viewed as most reflective of overall environmental pressure (Lutter and Giljum, 2014; Kovanda, 2020), however is also associated with greatest uncertainty. TMR was calculated for the UK as part of the ONS Environmental Accounts up to 2013.

[126] An Environmentally-Extended Multiregional Input-Output (EE-MRIO) model is an integrated dataset combing a monetary multi-regional Input-Output table (MRIOT) representing monetary inter-industry and inter-sectoral flows within and across regions, and an extension table in physical units depicting environmental flows 'inputting' into with those economic activities in a similar way to labour (Lutter and Giljum, 2014; Wieland et al. 2019).

[127] EE-MRIO has been used in scenario modelling to study the effects of changes in an economy on emissions, raw material consumption, employment and value added within a context of industry and final demand interdependencies. Aguila-Hernandez et al. (2018) document approaches using EE-MRIO which attempt to assess the impacts of change in residual waste management, supply chains, product lifetimes and resource efficiency, with examples of relevant work at the level of individual economies (e.g. Barrett et al. 2009; Scott et al. 2019; Norman et al. 2021) as well as the global economy (Wiebe et al. 2019; Donati et al. 2020).

[128] This measure of RMC captures primary raw material extraction in a given year driven by domestic final demand and does not include secondary raw materials obtained from the pre- and post-consumer phase. This point cannot necessarily be generalised to measures of EW-MFA, for which secondary material flows may be captured in traded components but which are not otherwise distinguished.

structures (as captured in domestic IO matrixes) for each region within a model in addition to bilateral trade relationships between them (Eisenmenger *et al*. 2016). Non-UK economic data has to date been derived from EXIOBASE with environmental extensions gathered separately, however issues exist with this source including that components of it are increasingly out of date and based on projections in many areas. In addition, due to the measure's comprehensiveness in attempting to capture full upstream supply-chains, its accuracy is thought to be relatively low compared to headline EW-MFA figures. By working at the level of products and sectors in input-output tables-which are characterised by relatively low levels of resolution-and with implicit assumptions of homogeneity in product outputs, potential distortions in results can arise through aggregation errors while limiting the level of disaggregation which can be achieved (Schoer *et al*. 2013; McCarthy, Dellink and Bibas, 2018). While drawing on official data throughout, the transformation process and statistical arbitrage involved in incorporating these sources into a EE-MRIO results in them being considered as effectively non-official data at present. This sits slightly at odds with the United Nations (UN) SNA-SEEA 2012 'Applications and Extensions' handbook, which recommends 'consumption-based indicators should be based on data and relationships contained in input-output tables; ideally…multiregional input-output tables should be used' (page. 17).

As with the meso-level, data on the total material stock of built capital in the UK or England was not identified. Furthermore, while EW-MFA focuses on the mass of materials at the interface between the economy and the environment, it does not account for meso-level flows of materials within the economy. Figures for total waste generation are released on a biennial basis by Defra, while the routes that waste are treated at a national level, both legally and illegally, are captured across a range of sources including 'Waste Data Interrogator', Incineration Monitoring Reports, export statistics and publications capturing illegal waste sites. Data on several treatment routes of total waste collected was found to be published by Defra, however gaps were found for other reverse loops such as remanufacturing or resale. Various measures of national circularity have been proposed (including CMUR and a measure based on RMC published by Circle Economy) alongside the introduction of a circularity target encouraged (Wrap, 2021) though one was not found to be currently tracked for the UK.

Impact data

Table 17 sets out data sources identified through our search capturing information on environmental, economic and social impacts at the national level. For those related to the environment, we include data on environmental pressures, the environmental stock and welfare impacts resulting from changes in these.

Table 17. Data assets relevant to the national level (physical impacts)

Dataset	What does it tell us in relation to this input requirement?	Publisher	Unit	Geographical extent and detail	Time covered, update frequency and lag (year)	Extra-geographical breakdown
UK National Atmospheric Emissions Inventory (NAEI)	Territorially-occurring GHG and pollutant emissions from the jurisdiction.	BEIS	Tonnes CO_2e	UK, Devolved Administrations	1990-2020, annual, 1	Gas (7), UNFCCC-defined sectors, category, source
Environmental	Tracks the most serious reported	EA	ordinal	England	2001-2022, annual, 1	4 category ordinal assessment

Pollution Incidents (Category 1 and 2)	pollution incidents the EA deals with.					Three environmental vectors: air, land, water. Locational data
Natural capital accounts	Estimates of the financial and societal value of natural resources to people in the UK.	ONS	£	UK	1997-2021, annual, 0.75	Flows (physical & monetary), assets (monetary)
Business Population Estimates	The most comprehensive data source on business numbers, employment and turnover in the UK and regions.	BEIS	£, Count	ITL1	2010-2021, annual, 0.75	Businesses Employment figures Turnover
Personal well-being estimates	Estimates of life satisfaction, feeling that the things done in life are worthwhile, happiness and anxiety in the UK.	ONS		UK ITL1,2,3	2015-2022, annual/quarterly, varies	4 categories of wellbeing
Social capital headline indicators	Current headline indicators for social capital in the UK. It includes the latest data for each indicator with time series and an assessment of change to track change over time.	ONS	%	UK	2011-2022, annual, 1.25	28 social capital indicators
Crime in England and Wales Statistics	Includes a question on the proportion of respondents perceiving litter or rubbish as a problem.	ONS	%	England, Wales	2001/02 - 2019/21, annual, 0.25	Breadth of questions relating to perceptions of crime

Annual territorial estimates for the release of the basket of seven greenhouse gases covered by the Kyoto Protocol (1990) are published by BEIS as part of the UK National Atmospheric Emissions Inventory. These are used in the UK's reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and form the basis for tracking progress towards the national 'net zero' target. Though in recent years territorial estimates have been published broken down by SIC code, these have historically been compiled in line with their end-use and for this reason, appear twice in this document. Waste management emissions are captured, though a criticism raised is that the accounting approach only considers direct emissions of sectors and not any contribution to emissions reduction - seen as particularly problematic for the waste management sector (Hogg, 2022; Harris and James, 2021). The Carbon Footprint statistics provide an important point of comparison, with potential reductions in these emissions reported in key studies exploring the possible impacts of changes in resource use e.g. Norman *et al.* (2021).

The experimental UK Natural Capital Accounts (NCA) expand the national balance sheet to account for non-produced territorial natural capital assets and the physical and monetary/monetized flows of services provided by these to the UK economy and society. There is an overlap between the flow components of the NCA and the UK Environmental Accounts of which the UK MFA is a component, albeit a greater emphasis on the physical annual flows of *services provided* by the natural environment in the NCA rather than *pressures placed* on natural assets. As Bright et al. (2019) state, "*in some instances, the two accounts mirror one another e.g. in the case of oil extraction, the use of which as an input into economic activities recorded in the EA equals the supply of provisioning services of oil from natural capital as recorded in the NCA…but in other cases, the relationship is not as direct*". The NCA attempts to also estimate the value and volume of regulating services e.g. waste remediation provided to people in the UK such as via the sequestration of carbon and cultural services including linked to recreation and contributions to built asset values (hedonic house price assessments). As well as tracking flows from natural capital assets, the source attempts to provide an estimate of the monetary value of NC assets measured as a function of the net present value (NPV) of the current and future flow of services they may yield based on agreed valuation timelines. Although estimates showing opening and closing timber stocks and components adding to and reducing these have been produced in the past, It appears there are no asset values published in physical terms as part of the Environmental Accounts at present. Other relevant sources identified include on sites of contaminated land.

Box 5. Measuring natural capital impacts of the circular economy

As one approach among others (IPBES, 2022), relations between the environment and people are increasingly framed through the ecosystem services (ES) concept, which offers a quantifiable model for illustrating the benefits that humans derive from the environment (Daily et al. 2009; Tanaka, Brunson and Torell, 2011; Bouwa et al. 2017; Smith et al. 2017). Things with the capacity to provide welfare now and into the future can be understood as stocks of capital or wealth, the value of which is a function of the net present value of the future stream of welfare opportunities it yields (Fisher, 1906; Hamilton and Hepburn, 2014). By giving rise to wellbeing directly via household production and indirectly via economic production (while in conjunction with human inputs), environmental economists argue that the environment can be seen as another form of capital alongside that built, human, social and financial (Barbier, 2015). It is furthermore argued that there is an imperative to incorporate information on natural assets into standard capital accounting frameworks in order to mainstream environmental considerations in economic decision-making (Obst and Vardon, 2014; Solow, 1993) and provide a more operationalizable measure of sustainability compared to the relatively nebulous tripartite framing based on balancing the systemic pillars of economy, environment and society dimensions (Solow, 1999; Barbier, 2010).

In its third report to the Economic Affairs Committee, the Natural Capital Committee called on the UK Government to develop: a national balance sheet of the value of natural assets; estimates of the depreciation of those assets where this occurs; and a redefinition of the way in which income and savings are measured *sensu* some of the initial and recently revived objectives of the SEEA-CF. Conducted at the request of the UK Treasury, the Dasgupta Review (2021) further asserts that tracking economic progress based on the overall value of capital assets would offer a better indication of the sustainability of the productive base than flow-measures such as GDP. The UK ONS now publishes estimates of the value of produced and non-produced non-financial assets, additional components of natural capital, net financial assets, human capital and indicators for social capital.

Natural capital maintenance and enhancement are presented as central to many definitions of the circular economy. However, being able to confirm not only the occurrence of this at the national-level but also the contribution of greater circularity to those impacts remains an area of ongoing development. The UK natural capital accounts in their present day form represent a significant step in improved consideration of nature in capital accounting frameworks, being published on a regular (annual) basis and covering multiple services across provisioning, regulating and cultural domains and implied asset values linked to these. In addition, new sensing technologies have enabled biophysical change in the natural environment to be measured in a more timely and detailed way than in the past. Nevertheless, an incomplete picture of the benefits nature provides to society remains due to conceptual and methodological issues, with the value of the likes of soil or biodiversity omitted. In addition and notwithstanding the Environmental Accounts role in capturing potential pressures placed on the domestic environment in physical terms, estimates of natural capital depreciation as well as macro- or mesoeconomic aggregates adjusted for that depreciation remains a gap. This is despite such presentations arguably being the most useful means by which natural capital considerations can inform decision-making including for entities who do not directly hold or manage assets. While depreciation (conceptually occurring at any rate of use for non-renewable assets or when use rates exceed those of renewal or assimilation for (potentially) renewable assets on the source or sink side, respectively) might in theory 'show up' in the NCA's service flows and assets, the sole presentation of assets in monetary terms at present means values are influenced by not only supply-side dynamics, but too those driven by demand (ONS, 2017). This can lead to potentially counterintuitive results wherein reduced demand leads to higher physical asset availability, but with a lower per-unit and thus overall monetary value. Chichilinsky (2000) has also shown that an expected utility approach is insensitive to unlikely but potentially catastrophic outcomes, while the marginal damage curve of depletion in many components of natural capital is highly uncertain and potentially subject to discontinuities (Dasgupta, 2008).

While the source ''UK Business: Activity, Size and Location" previously introduced is recommended by the ONS as the most robust data for industry-level estimates of business numbers and related parameters, these figures include only businesses registered for VAT/PAYE which can lead to small businesses (<£85,000, correct 28/06/22) being omitted. Therefore, the BEIS publication 'Business Population Estimates' (BPE) is recommended as the best source of data to gauge the total business population and associated jobs and turnover in the UK as it includes an estimate for businesses unregistered through the VAT/PAYE system.[129] The BPE also provides measures of statistical accuracy including for regional and industry-level breakdowns, though caution is advised in using the data as a time-series due to inconsistencies in the sources and timing of updates for inputs.[130]

Although sources presented in this document capturing monetary exchange value correspond conceptually to economic welfare, wellbeing is distinct by including aspects which cannot be traded in markets such as happiness and satisfaction (IMF, 2020). Wellbeing can be understood objectively in terms of the circumstances of a person, their income, life expectancy and environmental quality or subjectively, in terms of personal judgements of these same circumstances, inclusive of one's own wellbeing, happiness and satisfaction. The 2018 HMT Green Book expands on the application of subjective wellbeing approaches in policy analysis. In addition and since 2011, the ONS has produced 'personal wellbeing' estimates at a UK-level as part of the Annual Population Survey (APS).[131] These are based on questions on how satisfied respondents are with their life or how worthwhile they see them as, as well as reported happiness and reported anxiety based on a scale of 0 to 10, with mean estimates and distributions produced and data provided to the level of counties, local and unitary authorities. Public perceptions of specific topical areas e.g. shortages of goods and perceptions of levels of crime (including littering) are also surveyed as part of ONS data relating to wellbeing and could offer useful insights in

[129]https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/businessregisterandemploymentsurveybresprovisionalresults/provisionalresults2020#measuring-the-data

[130]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1018138/bpe_methodology___quality_note_2021.pdf

[131] The APS is a continuous household survey covering the UK, with the aim of providing estimates between censuses of impotent social and labour market variables at a local level. The achieved sample size of the survey is approximately 320,000 respondents (ONS, 2020).

areas greater circularity may affect. Measurement complexities and recognition of potentially flawed assumptions of interpersonal subjective comparability need to be kept in mind.

Many of the monetary sources outlined present data on activities set within the boundaries of what is understood to be 'the economy' (SNA, 2020). However, many activities making up the CE do not necessarily cross that measurement threshold. While guidance has been published to track wider non-market activities (which may form a key part of CE activities e.g. repair as part of household production) through satellite accounts such as in the 2018 UN Handbook of National Accounting: Satellite Account on Non-profit and Related Institutions and Volunteer Work, activities falling outside of non-profit institutions are largely invisible in official statistics. Statistics of social capital as published by the ONS include estimates of the percentage of respondents engaging in public volunteering alongside figures on trust and cooperative norms and personal relationships. Figures on human capital are also published separately.

Summary

At the national level, and as what constitutes a fairly rigorous, systematic and comprehensive accounting framework (Malinvaud, 1973), the National Accounts describe a range of variables captured at different measurement points and sectors across the economy on a regular basis and constitute a relatively comprehensive source as a result. While so, identified gaps at the meso-level for demarcating activities commonly associated with a more circular economy stand to undermine the comprehensiveness of national-level estimates of associated output, value-added or jobs and, in turn, comparisons with the more linear economy.

For material flows at the national-level, there is a relatively comprehensive picture for variables of interest across the linear value-chain with exception to the use phase. At the inflow stage, the Material Flow Accounts capture apparent flows of materials (excluding e.g. water) into the economy, while measures of the national material footprint capture the full upstream material extraction driven by domestic final demand. At the outflow stage, statistics on total national waste generation are published on a biennial basis, while data on legal and illegal routes by which waste is treated are published more regularly, albeit with gaps around many reverse-loop activities. No measures of national circularity or physical stocks were identified.

A breadth of impact-related data covering pressures potentially driven by material flows, changes in stocks and societal impacts of these were identified, as well as wider impact categories such as on perceptions of waste crime, personal wellbeing and social capital. Due to the limited granularity in many of these e.g. by geography, it would likely remain difficult to attribute change in some categories due to circular-economy driven transformations, an issue which can also arise through the unit by which data is presented in e.g. the monetary value of natural capital assets.

2.6 Timeliness aspects

Reviewed data sources varied in terms of:

1. **Timeliness** - At the time of this assessment and of the data assets reviewed for which a date of last update was provided on its respective landing page or within the data file itself, **61%** had been published within the last year and **81%** within the last three years.
2. **Lag time** - The time between the date of publication for a given source and the last period to which the data referred varied between 1 month and over 3 years, with the average lag time

across sources, 1 year. Higher lag times can pose difficulties for more timely decision-making, but in some cases appears difficult or costly to avoid due to dependencies on other sources e.g. national SUTs as a culmination of a breadth of surveys and inputs.

3. **Regularity of updates** - The most frequent interval between publications across sources was annual (**59%**). A smaller proportion were published on a less than annual basis and predominantly a quarterly or monthly basis (approximately **16%** across both). A fifth (**22%**) were published on an ad-hoc basis meaning the interval between publications would vary. In a few cases, data were updated on a biennial or longer interval.
4. **Temporal coverage** - Temporal coverage varied between sources, with the median coverage 16 years (mean = 19) but ranging between single-year snapshots to over 50 years worth of continuous data. In some cases, far more historic data were available but through archival systems e.g. the UK Minerals Yearbook providing data stretching back to 1853.
5. **Continuity of publication** - For the majority of reviewed sources on established publication cycles, a future publication appeared to be expected. This was not always easy to discern as in only a few cases were dates for future releases provided and this was mainly from those sources released on relatively regular cycles e.g. monthly or quarterly. Sources such as administrative statistics could broadly be expected to continue to be published. For non-administrative data, planned discontinuations were identified in a handful of cases. In some cases, sources had already been discontinued such as for the MRIO Exiobase, which at the time of writing the last years of real data were several years prior and with any updates since based on nowcasting and in some cases, this also ceasing.

3. (Meta)data and infrastructure fitness

Here, we assess shortlisted data assets against characteristics which can enhance the net benefits of their use and reuse within an observatory assessment and monitoring framework. This is done to help identify systemic gaps and issues in the data ecosystem where general improvements could potentially be focussed to help enable most net-benefits to be derived.

3.1 FAIR +

'The ultimate goal of [the] FAIR [principles] is to optimise the reuse of data' (GO FAIR, 2022). Data, metadata and data infrastructure reflecting the FAIR principles can help reduce barriers to incorporating data into an analytical workflow and deriving value from it. Here we present results of an assessment of assets identified as relevant to the assessment framework against the FAIR principles primarily using tests from the FAIR Evaluation Service Tool. More on this methodology can be found in Appendix 1.

Findability

To be able to make use of potentially valuable data within an observatory assessment and as part of the proposed monitoring framework, it first needs to be discovered. An excessively fragmented evidence base navigable only through high levels of domain expertise can ultimately detract from potential inputs being found and value from them, leveraged. According to the FAIR principles, the findability of a data asset is largely a function of its identifier scheme, informative (and machine-readable) metadata and effective indexing within established search infrastructure. Here, the extent of our focus is on documents made available in a digital format and we consider the ease with which both humans and computers can find the (meta)data assets identified as relevant to the assessment framework.

A globally unique and persistent identifier helps find and retrieve (meta)data from an established location, cite it and maintain sight of related outputs in support of enhanced provenance. All (**100%**) assessed assets were found to have a unique identifier (URL) which could support this. Despite asset identifying schemes such as DOI supporting content persistence more reliably than URLs, in only a few cases (**0%**), was the identifier for a data asset or its associated metadata tested to be likely persistent.[132]

Data assets being richly and consistently described in metadata can further support their findability. Rich/comprehensive, standardised and machine-readable metadata (broadly separable into that descriptive, administrative and structural) enhance the findability of an asset, understanding of its provenance and other aspects such as timeliness. By labelling data to be readable by both humans and computers, machines can play a role in helping search for, organise, reuse, combine and synthesise information rapidly (Balbi *et al*. 2022).[133] A test for the ability of a machine to identify 'structured metadata' (e.g. RDFa or json-id facilitating the storage of metadata) associated with an asset was passed by **88%** of

[132] Additional assessment of the robustness of the test for a DOI is needed and this result should be viewed as preliminary. In addition, though less machine-readable, it is also recognised that some organisations have in place processes to ensure long-term access to data such as through archival systems. This was not uniformly the case however and persistence of data was found to be poor in some areas such as historical waste composition surveys.

[133] Metadata harvesting is a process of a 'data harvester' collecting metadata from a 'data provider' (Breeding, 2002). This can involve the use of automated tools and approaches to discover the semantics of data elements and determine whether sources are relevant to a particular enquiry (Wikipedia,). A range of techniques including semantic similarity analysis can help reduce the need for precise lexical matches.

successfully tested assets, while a marginally higher proportion (**90%**) successfully passed a test for the ability of a machine to identify 'grounded metadata'. Meta(data) clearly and explicitly pointing to the identifier of the data they describe can further support findability of data assets, particularly as metadata and data are often stored as separate files. Though a relatively simple criteria to fulfil, only half (**52%**) of assessed digital assets were found to have their metadata contain the unique identifier of associated data, while in no case (**0%**), was returned metadata found to contain an identifier for the metadata iself.

Across the public repositories examined, metadata was found to vary in schemes used and completeness. API requests made to data.gov.uk returned 62 metadata fields while those made to the ONS site returned a narrower number of metadata fields (n=20) for the few sources accessible via API. Poor consistency in metadata identifiers both at the level of fields and values under these was found while across both catalogues, metadata fields were found to be left blank reducing their descriptive value and usefulness in filtering.

The findability of data can further be increased by (meta)data being registered or indexed in a searchable resource, with rich and consistent metadata supporting this. Searchable resources can take forms ranging from domain- or publisher-specific catalogues to generalist public repositories. For the former, having consolidated and effective digital infrastructure in place to search for assets, and for the latter, assets being easily findable through established search engines (including through (meta)data being effectively indexed across both), contribute positively here. For some inputs, fairly high domain-specific knowledge was required to find sources including due to not being easily retrievable in search infrastructure with key words. Additional exploration was often also required to identify variables of relevance. Data management practices varied across the domain/entity-specific infrastructural assets searched, with version control systems found to be more developed for the ONS website (and others looked at e.g. the UK Data Service) than for data.gov.uk.

In summary and across the reviewed (meta)data assets, none successfully passed all tests for characteristics of findability, with the spread of results (across 8 tests) ranging from 1 to 5 and averaging 4. The most widely passed test was for the presence of a unique identifier, while the most widely failed tests were for the likely presence of a persistent identifier or the inclusion of an identifier for metadata within a metadata entry itself. The overall implication of the highlighted issues around findability, is that discovery of relevant data sources can take a significant amount of time, frequently requiring manual intervention, and in some cases sources which could have otherwise added value are missed.

Accessibility

Once a relevant (meta)data asset has been discovered, the next step in potentially making use of it is to determine its accessibility. There has been a concerted drive towards greater accessibility in public data assets in line with The Public Sector Bodies (Websites and Mobile Applications) Accessibility Regulations 2018 (the "accessibility regulations") (BEIS, 2022). Specifically in relation to the FAIR principles, the potential accessibility of (meta)data assets is enhanced through being retrievable by an identifier using a standard communications protocol which is: 1) open, free and can be universally implemented; and 2) allows for authentication and authorisation, where required.

For a human user, a standard communications protocol broadly translates to the ability to access at least the metadata associated with a data asset using a computer and internet connection e.g. via HTTP(S), FTP or similar (i.e. a standard search and click approach). For a machine, access/retrieval would ideally be possible via a standard web service application programming interface (API), though web-scraping methods can achieve the same. The FAIR principles emphasise clear communication of access conditions or restrictions rather than data openness in and of itself, and where (meta)data might be particularly sensitive, supplying contact information (e.g. an email) for a data manager to enable a user to access further information about a data asset is taken as acceptable. For all reviewed data assets (**100%**), the associated metadata was tested to be retrievable using an open protocol for both humans and machines and their communications protocol allowed for an authentication and authorisation procedure, where required. Half (**53%**) of shortlisted data assets were found to be retrievable using an open protocol for both humans and machines and allow for authentication and authorization, where required, in the resolution protocol for retrieval.[134]

Whilst ideally data might remain accessible online for some time in order that it can be retrieved for future use, significant curation and storage resources can be required to do so. In addition, versions of data can become superseded for a variety of research. Therefore, the FAIR principles emphasise the long-term archiving of metadata such that more complete indexes of past and current data assets are retained. In a test for whether any assessed (meta)data asset retained a persistence policy, this was not found to be the case for any reviewed metadata assets i.e. **0%**.

In summary, no reviewed (meta)data asset successfully passed all tests relating to accessibility, with the spread of results across 5 tests ranging from 2 to 4 and averaging 3. The most widely passed test was for metadata retrieval being possible using a standardised communications protocol followed by a communications protocol being in place to enable authentication and authorization for access to (meta)data, if required. The most widely failed test was for the presence of a metadata persistence policy.

Openness

The FAIR principles are equally applicable to data made available on an open or closed basis. Data openness norms and practices have grown in recent years across a range of domains, evolving from an initial focus on the use of open data file formats to a wider emphasis on the utilisation of open standards across (meta)data components and classifications. While in some cases, data cannot be made available with the technical and legal characteristics to support open and free use and reuse or would require significant resources to do so,[135] by doing so, it removes barriers to its incorporation into a range of applications.

The 'openness' of (meta)data assets was assessed here on the grounds of being: *free* to access and any requirements around use likely met by intended applications under the observatory; being published in a non-proprietary file format; and there being in place a licence enabling open onward reuse with minimal conditions. Given our search's slant towards data sources released by public actors, only a few of the relevant identified data assets were made available on a commercial paid basis or had conditions in place

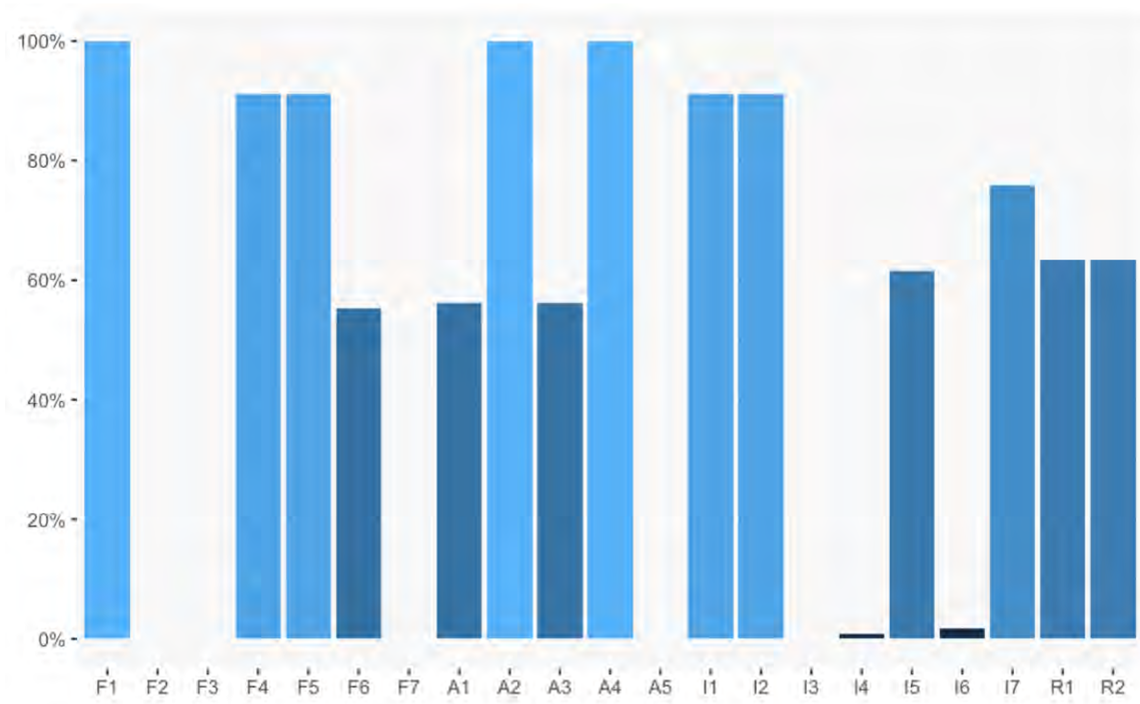
[134] An API was in place for two of the examined public data catalogues (data.gov.uk and the ONS website) for helping users access (meta)data programmatically, though at differing stages of development. The ONS' API was found to allow for relatively complex querying of data including choices between editions/versions while enabling access to individual observations. Not all (meta)data otherwise published by the organisation could be accessed programmatically however, and at the time of this review, 20 data assets were found to be returned via the ONS API, 4 of which were data assets shortlisted as relevant to the input requirements outlined. In comparison, while the data.gov.uk API gave access to metadata, this did not extend to data itself being queryable in a machine-readable way. APIs at the level of data assets themselves were found for _ data assets.

[135] In practice, a range of issues relating to confidentiality can limit the degree of potential openness in the level of detail provided across data collected. De-identification and aggregation with an associated loss of detail can often be difficult to avoid. In addition, firms rarely have an incentive to share data outside of that mandated/expected or which will increase their bottom line due to concerns around competitiveness and liability. It is recognised that collecting and publishing data has costs and public good characteristics present a challenge to recouping these (Pollock, 2006).

regarding who could access it and which uses under the observatory did not meet.[136] In summary, effectively all (**99%**) data assets provided access to their data for free[137] while **97%** could be accessed, used and reused based on the planned applications as part of the observatory framework. While file formats varied, the vast majority (**>85%**) of assets were made available in a non-proprietary format (e.g. XLSX, ODS, CSV and PDF) while for the few sources using proprietary file types, these included XLS and accdb.

For sources where a reference was identified (the vast majority), **77%** were published with an Open Government Licence or equivalent e.g. Creative Commons, **9%** with bespoke terms and conditions anticipated to be met by intended use and **7%** with an Environment Agency Conditional Licence. Users could benefit from greater consistency in the clarity of use licence presentation across repositories and sites - something done well by the likes of data.gov.uk.

Figure 7. Proportion of (meta)data assets passing each binary compliance test for FAIR principle alignment (tests defined in the Appendix)



Interoperability

Whether as part of a single layer of assessment or across several, applying the observatory analytical framework generally requires the integration of information from various sources.

Interoperability refers to the ability of different systems to accurately and unambiguously exchange data (Geospatial Commission, 2022). Machine-readability at the level of data itself through the selection of

[136] These restrictions required potential users to meet explicit in-group conditions including being part of a specific industry-group (IDIS) and in addition, being willing to supply data (e.g. the Material Pricing report).
[137] For the purpose of this review and for a given asset, if a sufficient amount of data was made available for free while payment was required for more specific or detailed information in particular areas, it passed this test.

machine-readable file types and consistent structures and formats increases interoperability and the efficiency of data analysis. In accordance with the FAIR principles, interoperability between (meta)data assets can be enhanced by: (meta)data being constructed and classified using a formal, accessible, shared and broadly applicable language for knowledge representation. This use of machine readable meta(data), well-defined metadata schemes (covering standards and models) and controlled vocabularies, taxonomies and ontologies consistent within a particular discipline increase standardisation and can support exchange and comprehension with minimal effort, including the identification of relevant (meta)data and its classification for particular applications.

The use of controlled vocabularies is endorsed by ISO 25964 on the basis that if both an indexer and searcher choose the same term for the same concepts, relevant information will be more easily retrieved. Across the data assets identified as potential inputs to the analytical framework, the vast majority (**90%**) were found to use structured metadata. The same percentage were tested to use in their metadata a formal language broadly applicable for knowledge representation interpreted in a general sense as one 'semantically grounded in ontologies'. Tests undertaken for whether terms in underlying data files were semantically grounded (which could be passed by any form of structured data) or contained 'ontologically-grounded linked data' were not passed in any case.

Metadata drawing on vocabularies that follow FAIR principles in themselves i.e. vocabularies which are well described, interoperable and linked to external definitions where ambiguous further contribute to interoperability under the FAIR principles. A test for whether metadata vocabularies resolved in general was passed by approximately three-fifths of tested data assets (**59%**) while a test to see if those metadata used terms resolving to linked FAIR data was failed in nearly all cases (excluding **2%**).

Lastly, where a dataset is contingent on another in some way or contains complementary information, the provision of qualified references to indicate this relationship can also support interoperability between (meta)data assets. Linking data sources through metadata can help user navigation, including through in-bound links back to a catalogue where similar data can be found or through out-bound links capturing various potential uses of that data. Scientific links can be expressed through relational ties e.g. 'A new version of' which can further be supported through suitable metadata fields. A test to see if shortlisted metadata linked outwardly to third-party resources was passed by roughly three-quarters of reviewed assets (**72%**).

In summary, across successfully tested (meta)data assets, none successfully passed all the tests used to assess interoperability, with the spread of results (across 7 tests), ranging from 0 to 4 and averaging 3. The most widely passed test was for the presence of structured metadata while the most widely failed tests were for data reflecting a broadly applicable language for knowledge representation and metadata terms resolving to linked FAIR data.

Reusability

The reuse of secondary data is a key part of being able to develop an evidence base as part of the work of the observatory. Under the FAIR principles, the reusability of data can firstly be enhanced through datasets being described within their associated metadata using a plurality of relevant attributes. This goes beyond facilitating the identification of relevant data (as captured in principle F2) to further determine the suitability of a source for an intended use. This determination can be on the basis of how the data was generated, why and by whom, its version, any reliability issues and in which contexts the information should be used (together constituting key parts of provenance). The reusability of data can further be enhanced by (meta)data meeting domain-relevant community standards in how it is structured, file formats used, standardised documentation and practices for data archiving.

Only one set of tests was available via the FAIR Maturity Evaluation for this criteria and related to the presence of a clear and accessible data usage licence. These ('weak' and 'strong' variants) tested for a pointer within metadata to a use/reuse licence, with approximately just more than half assets identified as relevant (**61%**) found to pass these. This indicates potential limitations on the clarity and accessibility of data usage licences at an individual data asset level in some cases.

Methodological transparency

With an aim of the NICER programme being to demonstrate the economic, social and environmental potential of circular economy (CE) interventions, communicating the level of confidence which can be assumed in any conclusions and recommendations made helps build trust in outputs. For the robustness of outputs to be communicated however, there needs to be an understanding of any uncertainties and potential inaccuracies associated with inputs alongside those coerced through a particular methodological design. There was not the scope to assess the quality of sources in terms of their accuracy/validity, objectivity or reliability here, and rather we examined transparency relating to any potential issues or uncertainty where appropriate.

Across the shortlisted data assets, more than half were found to communicate uncertainty or methodological issues qualitatively in written documentation, though how this was done varied across publishers and in some cases this information had to be requested. For the share of datasets for which the quantitative assessment of uncertainty (such as through the inclusion of standard errors or response rates) was appropriate, this was not especially widespread. In many cases, sources were found to be released with an endorsement/badging of quality such as 'Official Statistics' or 'National Statistics' indicating quality assurance in production. No source was found to be published alongside code used to produce them so as to enable reproducibility/repeatability.

Glossary

Bill of materials	A hierarchically structured list of materials, components and parts making up a product alongside their quantity and costs
COICOP	The Classification of Individual Consumption According to Purpose (COICOP) is the international reference classification of household expenditure
CN	Combined Nomenclature (CN) - the EU system for classifying products used to collect trade data through customs procedures (ONS, 2020)
Data	Factual information (such as measurements or statistics) used as a basis for reasoning, discussion, or calculation
Data ecosystem	The people, communities, and organisations that are stewarding data, creating things from it, deciding what to do based on it, influencing any of those activities, or are affected by any of those activities (ODI, 2019)
Data infrastructure	Made up of data assets, standards, technologies, policies and the organisations that steward and contribute to them (ODI, 2019)
Domestic material consumption	The used fraction of domestically extracted and harvested materials and imported raw materials, semi-finished and manufactured products, excluding the weight of exported raw materials, semi-finished and manufactured products. Otherwise referred to as apparent consumption.
Domestic used extraction	Flows of materials originating from the domestic environment and which enter the economic system for further processing or direct consumption
Direct material input	Direct input of materials for use in production and consumption activities, including the production of export goods and service, equalling domestic extraction used plus imports
Economic production	Any activity carried on by an institutional unit which uses inputs of materials, labour and capital to produce output of goods and services
Key performance indicator	Metrics used to monitor, assess and report on dimensions of [potential] change identified as of importance to stakeholders. Help track performance, including against objectives, support learning and provide a common unit to assess the desirability of different configurations
Industry	Establishments engaged in the same kind of economic activity (SNA, 2008)
Intensity indicators	“Intensity indicators compare trends in economic activity such as value-added, income or consumption with trends in specific environmental flows such as emissions, energy and water use, and flows of waste. These indicators are expressed as either intensity or productivity ratios, where intensity indicators are calculated as the ratio of the environmental flow to the measure of economic activity, and productivity indicators are the inverse of this ratio.” (SEEA-Environment Extensions, 2012, pg. 13)

Footprint	A technique through which environmental pressures, including beyond territorial boundaries, are attributed to domestic demand
Gross domestic product	'combines into a single figure…[the monetary value of] the [market] output…carried out by all the firms, non-profit institutions, government bodies and households in a given territory during a given period, provided that the production takes place within the country's economic territory' (OECD, 2014, p.15). GDP is a headline measure of the SNA and the most widely used metric for measuring national economic development at present. Reference to economic growth today is generally in reference to the level of output in an economy relative to prior years as measured by inflation-adjusted GDP
Institutional units	Economic entities 'capable of owning assets, incurring liabilities and engaging in economic activities and in transactions with other entities' (Lequiller and Blades, 2014)
Machine readable data	Data in a data format that can be automatically read and processed by a computer (Open Data Handbook)
Material processed	A measure of secondary materials (i.e. previously processed) inputs in addition to primary material inputs entering domestic production and consumption activities
Metadata	'Structured information describing, explaining, locating or otherwise making it easier to retrieve, use or manage an information resource' e.g., the Dewey decimal system of library asset categorisation. Used to discover properties of data
Natural resources	Nonproduced naturally occurring assets, where nonproduced means that the assets are not thought to have been created by an economic production process (UN SNA 2008)
Net additions to stock	The mass of materials added to the economy's stock each year (gross additions) in buildings and other infrastructure incorporated into new durable goods such as cars, industrial machinery and household appliances net of materials removed from the stock as buildings demolished and durable goods disposed of
Physical input-output tables	Physical input-output tables (PIOT) describe the flows of material and energy within the economic system and between the economic system and the natural environment (Eurostat, 2001)
Primary raw materials	Virgin materials resulting from extraction
Product	Processed or finished items offered for sale as materials, components, assemblies or final product and other products
Secondary raw materials	Recycled materials obtained from pre- and post-consumer phase in the technosphere
Raw material consumption	Raw material consumption (RMC) or 'material footprint': A measure of domestic used material extraction in addition to the full upstream used

	material extraction associated with the production of imports, while excluding that associated with exports. In other words, the allocation of global used raw material extracted to meet final demand in an economy in a given year, thereby including the full used primary raw materials associated with the production of or ‘embedded’ within, imported products
Raw material input	The raw materials associated with production and consumption activities, including the full raw material equivalents along international supply chains
Standard industrial classification	‘The UK Standard Industrial Classification of economic activities, abbreviated as UK SIC, is a five-digit classification providing the framework for collecting and presenting a large range of statistical data according to economic activity.’ (ONS)
System of National Accounts	The internationally agreed standard set of recommendations on how to compile measures of economic activity, particularly geared towards the development of aggregates (UN STATS)
Taxonomy	A hierarchical classification of entities of interest in an enterprise, organisation or administration, used to classify documents, digital assets and other information
Total material requirement	Equivalent to DMI plus displaced materials due to extraction, harvesting or cultivation that do not enter the economy
Waste	Any substance or object which the holder discards or intends or is required to discard (Directive 2008/98/EC Article 3(1))
Waste disposal	Final deposition of waste above or underground in controlled or uncontrolled fashion (Eurostat, 2021)
Waste management	Activities and measures which prevent the generation of waste and reduce the harmful effects of waste on the environment (Eurostat, 2021)
Waste treatment	Processes which change the physical, chemical, or biological character or composition of waste to render it non-hazardous, safer for transport, amenable for recovery or storage, or to reduce it in volume. A particular waste may undergo more than one treatment process (Eurostat, 2021)
Value added	Economic value can be understood as being created through production activities, with ‘value added’ what remains after the costs of production are accounted for, from which income e.g. wages or share dividends is derived. This income is then either spent or saved as financial or non-financial assets and in some cases re-lent back into the economy

Appendix (I) - Review protocol and weaknesses

The objective of the working paper is twofold. Firstly, it aims to examine the current coverage of publicly accessible data in relation to the input requirements set out in section 1. This is to help understand whether there is already in place a sufficient statistical basis from which to be able to monitor and model the occurrence and value creation potential of greater circularity using the analytical framework developed by the CE-Hub and in doing so, help answer stakeholder questions. We recognise that there are reasons why data can be made available on a commercial or otherwise restricted basis, however this scope was adopted to make this initial assessment manageable. Secondly, the paper aims to assess shortlisted data assets against characteristics identified as increasing data fitness and enabling value to be leveraged most effectively from them.

To achieve these objectives, the review protocol is executed in two overarching phases. Firstly, (meta)data assets of relevance to the required inputs are searched for and filtered to arrive at a shortlist, relevant metadata for which are inventoried and curated further in terms of scale, area of focus, unit, timeliness aspects and disaggregation among other fields. A qualitative gap assessment in relation to the input requirements is then made within the report. Secondly, shortlisted data assets are scored against the characteristics identified as being able to add value to processes in which they are used. This allows strengths and limitations around data fitness to be assessed quantitatively and provides the potential future basis for comparison across, for instance, value chain stages and scales.

Approaches adopted in the literature

Several assessments of data for use in monitoring and modelling across a range of related areas have been undertaken to date:

1. The BRASS Centre for Defra undertook a critical review of data capturing the environmental impacts of household consumption (2006), finding economic data more widely available and robust than that relating to environmental impacts. For data on environmental impacts that were available, this tended to reflect one dimension such as GHG emissions rather than a holistic picture.
2. As part of the CREDs programme, Norman *et al*. (2020) reviewed publicly available datasets related to industrial energy emissions in the UK, finding issues including: a lack of detail for many sub-sectors of interest; irregular updates; limited accessibility across many datasets; problematic transparency in methods, sources and assumptions; and inconsistencies in the use of classifications, taxonomies, units and formats together rendering current data insufficient to support robust and timely analysis and monitoring.
3. Burger-Scheidlin *et al*. (2021) assessed the current implementation of FAIR and open data and metadata practices in databases relevant to the low carbon energy domain at an EU level, finding issues with the ease by which data could be found as well as poorly recorded provenance and reuse permissions.
4. In populating a raw materials flow analysis for key raw materials at the European level (EC, 2012), Bio for Deloitte (2015) analysed available data sources, finding: gaps around supply and demand trends; issues with accuracy and inconsistencies in source databases; out of date, highly aggregated and imprecise product codes alongside limited information of average material makeup for codes tracking waste; and an absence of explanatory metadata.

Other assessments identified in the literature include BRE's Construction Resources and Waste Compendium Annex 1. The approach taken in these assessments have informed that adopted here.

Search methodology

The UK's modern public statistical landscape has been characterised in the past as being devolved across UK political administrations and decentralised across data issuers within its countries (Dunnell, 2007). While quite a number of online public catalogues exist in the UK for users to find and retrieve data public assets across geographies and topics of interest (with several of these set out in Table 18), several catalogues or repositories have sought to consolidate available data e.g. data.gov.uk.

Table 18. Examples of public data catalogues in the UK

Catalogue URL	Geographical coverage	Quoted description/purpose
Gov.uk	UK	*"The best place to find government services and information"*
data.gov.uk	UK	*"Find data published by central government, local authorities and public bodies to help you build products and services"*
ons.gov.uk	UK	*"UK's largest independent producer of official statistics and its recognised national statistical institute…responsible for collecting and publishing statistics related to the economy, population and society at national, regional and local levels"*
ukdataservice.ac.uk	UK	*"House the largest collection of economic, social and population data in the UK."*
bgs.ac.uk	UK	*"UK's premier provider of objective and authoritative geoscientific data, information and knowledge"*
Wrap.org.uk	UK	*"Working with governments, businesses and citizens around the globe to create a world in which resources are used sustainably"*
statswales.gov.wales	Wales	*"a free-to-use service that allows you to view, manipulate, create and download tables from Welsh data."*
lle.gov.wales	Wales	*"Serves as a hub for data and information covering a wide spectrum of topics, but primarily around the environment."*
sepa.org.uk	Scotland	*"We publish a range of datasets related to the environment."*
opendatani.gov.uk	Northern Ireland	*"Created to facilitate easy access to Northern Ireland public sector data for both reuse and redistribution."*
data.london.gov.uk	London	*"A free and open data-sharing portal where anyone can access data relating to the capital"*

For the purpose of this initial assessment, we did not look at data specific to Wales, Scotland or Northern Ireland, rather focussing on sources capturing information on the UK as a whole and England specifically. Care should therefore be taken in generalising any findings. To establish a longlist of potentially relevant data assets, a set of search terms (as set out in Table 19) were first selected to reflect data input requirements of the observatory framework. These were then entered into two of those catalogues listed in Table 18 selected for their comprehensiveness and appropriate to the geographical scales of interest (data.gov.uk and the ONS site). This was done between August and October 2022.

Table 19. Search terms used to identify assets

Value chain stages and material flows and stocks-specific	Economic dimensions[138][139]	Impacts[140][141]
Mining Refining Processing Manufacture Assembly Distribution Usage Waste Collect Disposal Maintenance Resale Refurbish Remanufacture Recycling Bill of materials Footprint	Trade Capital formation Prices Output Turnover Revenue Profit Value added Register	Emissions Natural capital Pollution Jobs Employment

Application Programming Interfaces (APIs)–which allow (meta)data to be accessed in a machine-readable way–were available in some form for most of the catalogues listed in Table 18, though only covered all sources registered in the data.gov.uk catalogue and not for the ONS site. Where relevant meta(data) could not be accessed programmatically (see further details in section 4), the search terms set out in Table 19 were entered into the web interface for the catalogue.

Table 20. Returned hits by search term and data catalogue

Search String	data.gov.uk[142]	ONS[143]
Mining	170	450
Refining	62	224
Processing	+1000	291

[138] Not otherwise captured by the search terms in column 1

[139] Several of these selected terms correspond to effectively the same thing at a conceptual level, but can be referred to in different ways at various scales of aggregation. For instance, profit is often referred to for an individual company, while value added is generally used for the same concept at the level of industries. We have therefore sought to avoid unnecessary exclusions due to such terminological differences

[140] Not otherwise captured by the search terms in column 1 & 2

[141] We did not use the search term 'energy' as the study by Norman *et al.* (2020) covers this extensively for the UK setting but did not exclude energy-related data assets where otherwise identified through our search steps

[142] Please note, a small difference in the number of returns using the API vs. the web interface was found

[143] result type: data. This included content of 'time series', 'datasets', 'user requested data'. Please note 'time series' will generally be a subset of 'datasets'

Manufactur*	146	1865
Assembl*	283	3
Distribut*	1000+	485
Usage	1000+	3
Waste	567	422
Collect*	1000+	125
Disposal	1000+	494
Maintenance	184	281
Resale	0	0
Refurbish	11	0
Remanufacturing	0	0
Recycl*	181	7
"Bill of materials"	0	378
Footprint	78	2
Trade	515	2395
"Capital formation"	1	4751
Price*	325	4130
Output	1000+	977
Turnover	77	343
Revenue	629	71
Profit	69	115
"Value added"	45	4386
Register	1000+	445
Emission*	413	514
"Natural capital"	10	4888

Pollution	642	30
Jobs	232	627
Employ*	167	1867

A large number and wide spread of digital data assets were returned across the search terms, overlapping across terms and repositories. The process returned a large number of resources determined to not be directly relevant to the observatory input requirements. To screen for these, a secondary manual sift was undertaken, excluding data assets viewed as not relevant on the basis of information contained in titles, descriptions and wider metadata entries to the extent possible. In some cases, data files themselves were examined, particularly where metadata was relatively incomplete. A subset of the shortlisted data assets captured from the repositories is presented in Table 21.

Table 21. Examples of shortlisted public-sector released data assets

Physical flows and stocks	Monetary/monetized flows and stocks	Impact[144]
Material flow accounts Prodcom HMRC trade statistics UK statistics on waste Consumption-based material footprint Fly-tipping incidents and actions taken in England Municipal waste composition Waste data interrogator National packaging waste database	Gross domestic product and gross value added Gross fixed capital formation by sector and asset National balance sheet Prodcom HMRC trade statistics Local authority revenue expenditure and financing England Environmental protection expenditures	UK National Atmospheric Emissions Inventory (NAEI) Atmospheric emissions: greenhouse gases and acid rain precursors Consumption-based GHG emissions Business Register Employment Survey Natural capital accounts

Several data sources known to cover information of potential relevance were not returned through this search process, as was also the case for data published by non-government actors. Therefore, the shortlist was supplemented by entering the same key terms into a major search engine (Google) in combination with the geographical reference terms ‘UK’ and ‘England’, with returned sources viewed as potentially relevant, added. Where additional data sources were known to the reviewing team or were

144 Within the language of the DPSIR analytical framework for human-nature interactions, pressures on the natural environment as determinants of the state of the environment and resulting impacts such as on human wellbeing are all encompassed here. By this understanding, impacts may be seen within those sources capturing physical and monetary flows and stocks listed in the first two columns too.

identified by reviewers, these were also incorporated. To make the scope of the assessment manageable and with exception to MRIO inputs, we did not actively search repositories of supra-national organisations such as the World Bank, UN or OECD though incorporated these sources where otherwise identified through the prior outlined search steps. This lack of comprehensiveness can be improved on in future studies. Through this process, a sizable number of data assets viewed as likely to be relevant as inputs into modelling and monitoring UK resource stocks and flows, emissions and wider impacts across the value chain at a micro, meso and macro level were shortlisted. The full list of these is set out in Annex 1, with this working paper curating them in further detail.

Data evaluation protocol

Data coverage

The coverage of data was assessed in a primarily qualitative manner on the basis of whether the search methodology outlined successfully identified relevant data assets able to provide a broad statistical basis to meet the input requirements of the observatory's analytical modules and KPIs. This included in a unit and form allowing data to be taken directly from source or with minimal adjustment such as the application of a deflator to monetary data. By broad statistical base, we sought data relating to flows and stocks of materials variously embodied in components and products across both linear and circular value stages covering extraction through to end of life and reverse flows. In addition, we sought to identify data characterising monetary value transfers and transactions between actors transforming and relaying materials and products covering variables such as sales revenue, gross value added, inventories, consumption, accumulation and prices in those same areas. At the impact level, we sought to identify additional data on social and economic dimensions including job numbers, job satisfaction, education, happiness levels and human capital, and environmental dimensions such as water use and pollution, greenhouse gases and energy, biodiversity impacts and wider natural capital effects.[145]

A qualitative approach was chosen for this step as the data requirements to populate the observatory approach are heterogeneous across cases for assessment, including in terms of geographical area, time periods and institutional units of focus and it was not possible to examine input availability in relation to all of these. Identified data assets were described in terms of what they were able to show, with gaps and issues summarised. A 'RAG' rating was used in some cases to broadly illustrate the coverage of data across value chain stages and different scales. This process allowed us to present a general picture of coverage while teasing out specific gaps.

Data fitness

In addition to examining the availability of data in relation to required inputs, we sought to assess shortlisted data assets against the characteristics outlined in section 1.3 as enhancing value from their use and reuse. Specific to the FAIR criteria dimension of this, a range of tools have been developed in the literature to assess the FAIRness of (meta)data (Bahim, Dekkers and Wyns, 2019). These assessments have also been undertaken across a range of domains, including by the UK government in its geospatial data (Geospatial Commission, 2022). We selected to use the semi-automated FAIR

[145] Natural capital refers to the stock of non-renewable e.g. metals and renewable e.g. forests elements of nature that directly and indirectly provide human beings with use, non-use and option values (Natural Capital Committee, 2013). Natural capital accounting (NCA) seeks to link quantification of natural stocks and changes within them into their welfare contributions to socio-economic activity (ONS, 2017).

Maturity Evaluation Service tool which consists of individual maturity indicators based on community-authored specifications against which tests can be undertaken using several small Web Apps. The outputs of these tests are a string of binary metrics reflecting adherence of a (meta)data asset to components of the FAIR principles (Wilkinson *et al.* 2019). For our purposes, we created a collection of maturity indicators on the FAIR evaluation site as a basis for this. In some cases, a test for searchability via an online web search failed, and this test was omitted and re-ran where this was the case. GUIDs representing a given data asset were selected as best as possible to capture all relevant metadata while ensuring specificity to a particular data file. Test results were true as of the 29th October 2022.

Several approaches have also been taken in the literature to assess data openness.[146]We take a fairly broad definition, focussing on data being available to access and use with no significant constraints in relation to anticipated applications as part of observatory workflows e.g. using data and publishing results based on it. We examined the openness of shortlisted assets against the following criteria therefore, with the first two effectively representing 'constraints' or binary inclusion/exclusion conditions given the focus of this assessment on publicly accessible data sources, and the latter two more so representing 'factors':

1) Data being free of charge to an end user;
2) Access to that data being universal i.e., access for anyone;
3) The presence of an Open Government Licence[147] or similar with minimal conditions to allow for open onward reuse; and
4) The use of a non-proprietary file format.

In some cases, sources were still presented in the text of this report where they were viewed as of particular interest, though accounting for restrictions to their use. The reason for this fairly relaxed interpretation of openness was so as to not exclude assets made available with minimally conditional licences that could be met by intended uses. As an extension of the FAIR 'reuse' criteria, the transparency of data assets in relation to uncertainty or methodological issues was assessed against three criteria:

1) Whether uncertainty/methodological issues were communicated:
    a) qualitatively e.g., in written documentation of strengths and weaknesses; or
    b) quantitatively, e.g., through the use of quality metrics or sampling error being communicated where appropriate e.g. in the case of probability-based survey data or more sporadic but comprehensive uncertainty assessments;
2) Whether a statement of quality assurance or equivalent was available; and
3) If code was made available to enable reproduction.

[146] For instance, the Open Data Institutes' 'Open Data Maturity Model' assesses organisational-level adherence to open data principles against five themes (data management processes, knowledge and skills; customer support & engagement; investment & financial support; and strategic oversight) with five progress levels within each. Berners-Lee alternatively proposed a '5 star deployment scheme' for open data ranging from simply making data available on the Web under an open data licence in any format, to making it available as structured data, in a non-proprietary format, using URIs to denote content and providing links to give context. Burger-Scheidlin et al. (2021) assess the openness of data assets using a four level scale ranging from data being fully publicly accessible by humans and machines using a standard protocol (open, with no log in), to being publicly accessible but requiring human intervention, being accessible to persons meeting stated conditions e.g., ethics approval for sensitive data, to not being open.
[147] The Open Government Licence (OGL) is assigned to allow free, perpetual licence without restrictions beyond attribution.

Lastly, the potential timeliness and continuity of inputs was examined in relation to whether the data had been updated within the last three years and was scheduled for a future release. These criteria are summarised in table 22.

Table 22. Examination criteria by dimension of quality

Criteria	Sub-criteria	Number	Test
	Findable (Ff)	F1	Presence of a unique identifier
		F2	A persistent metadata identifier
		F3	A persistent data identifier
		F4	Structured metadata
		F5	Grounded metadata
		F6	A data identifier made explicit in metadata
		F7	A metadata identifier made explicit in metadata
	Accessible (Fa)	A1	Retrievable data with a standard communications protocol
		A2	Retrievable metadata with a standard communications protocol
		A3	Data authentication and authorization available, as required
		A4	Metadata authentication and authorization available, as required
		A5	Metadata persistence
	Interoperable (Fi)	I1	Metadata knowledge representation language (weak)
		I2	Metadata knowledge representation language (strong)
		I3	Data knowledge representation language (weak)
		I4	Data knowledge representation language (strong)
		I5	Metadata uses fair vocabularies (weak)
		I6	Metadata uses fair vocabularies (strong)
		I7	Metadata contains qualified outward references
	Reusable (Fr)	R1	Metadata includes licence (weak)
		R2	Metadata includes licence (strong)
Openness			Free to access
			Open to anyone
			Presence of an Open Government Licence or equivalent

	Use of non-proprietary file format
Transparency	Quality/methodological issues communicated qualitatively
	If survey-based, quantitative quality metrics such as standard error, coefficient of variation and response rate
	Statement of quality assurance available
	The availability of code to enable reproduction
Timeliness and continuity (C)	Update planned
	Published in last 3 years

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