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Between 2010 and 2021, global emissions from digital technologies were largely obscured in greenhouse gas emission accounting standards

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The climate impact of digital technologies remains insufficiently measured. Using global input-output data, we calculate the embodied –i.e., supply chain-related– greenhouse gas emissions of digital industries (hardware, IT services, and communications). We find that the total embodied emissions of digital industries in 2021 are 4.1% of global emissions, with 77–87% being accounted for upstream (i.e., under Scope 3 of the Greenhouse Gas Protocol). We show that 42% of digital emissions are ultimately accounted for within non-digital industries. Hardware accounts for the largest share of digital industries' embodied emissions, while increasing demand for IT services has driven emissions growth over the past decade. Our findings highlight the need to reduce digital emissions across all industries' value chains. This includes accounting for embedded digital inputs, adopting circular economy principles in hardware manufacturing, and limiting embodied emissions from IT services, such as artificial intelligence.

We are currently witnessing profound technological change driven by the widespread adoption of digital technologies[1]. However, systematic assessments of the environmental consequences of digital technology adoption remain limited and vary greatly [2–5]. This limitation also applies to the measurement of the embodied emissions of digital technologies (e.g.[6,7]), i.e. the greenhouse gas (GHG) emissions associated with the lifecycle of a product or service from cradle to gate—covering product or service development, raw material extraction, processing, manufacturing, and assembly.

Two principal approaches exist for calculating the embodied GHG emissions of products, services, or entire industries. On the one hand, bottom-up approaches model production processes and emissions by starting with individual components or devices and aggregating their contributions. For instance, using a bottom-up approach primarily based on data from 150 companies combined with Life Cycle Assessments (LCA), Malmodin et al.[6] and Ayers et al.[8] report global GHG emissions of the information and communication technology (ICT) sector of 1.4% in 2020 and 1.7% in 2022, respectively. However, LCA studies tend to suffer from incomplete accounting (truncation bias), as there is a cut-off point beyond which activities are not included in the model. Freitag et al. conduct a systematic literature review of GHG emission estimates for ICT. By adjusting previous bottom-up LCA estimates for possible truncation bias using additional input-output (IO) analysis, they conclude that the global climate footprint of digital technologies in 2020 is likely larger—between 2.1 and 3.9% of global emissions[7].

Environmentally-extended IO analysis is the second approach for analyzing embodied emissions. It leverages macroeconomic tables that capture the flow of goods and services and their associated emissions between sectors (see Methods section for details). Using these tables, total global emissions are allocated to economic sectors in a top-down manner, thereby capturing value chains more comprehensively [9]. Applying Inter-Country Input-Output (ICIO) data from the OECD, Yuan et al. find that digital technologies accounted for approximately 4.0% of global emissions between 2005 and 2019 when comprehensively considering upstream and downstream emissions[10]. In addition, applying the World Input-Output Database (release 2016), Dong et al. report for 15 selected countries that digital industry embodied emissions accounted for 89.86 Mt, or 0.32% of global embodied CO2 emissions in 2009[11].

The standard IO approach, which relies on the Leontief inverse matrix that represents the input that each industry requires from other industries to meet one unit of demand, however, has limitations. It can only be used to calculate embodied emissions associated with the final demand of industries, e.g. household or government consumption (see Supplementary

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Table 1 for categories of final demand). It cannot be used to calculate the emissions that digital technologies induce as intermediate inputs in the production of products and services in traditionally non-digital industries, such as automotive or finance. Thus, the main contribution of this paper is to overcome this limitation of the standard IO approach by quantifying the hidden emissions associated with digital technology inputs in non-digital industries. Unlike embodied emissions that are linked to digital final demand and therefore clearly attributed to the digital industries, those transferred to non-digital industries are hidden in the sense that they do not appear explicitly as digital emissions in the emissions of the final demands of non-digital products and services. The relevance of such embedded emissions has been pointed to in previous studies[7,10]. We identify these hidden emissions by extending the standard Leontief approach by an innovative iterative calculation method numerically comparable to Cabernard et al. (15) but with the distinctive advantage that it produces an adjusted Leontief inverse corresponding to the productions needed to meet one unit of intermediate and final demand of any individual sector or grouping of sectors (for a detailed explanation see the Methods section). Using this approach, we reveal underlying drivers, scopes, sources, and geographical distributions of changes in embodied emissions of digital industries in the economy in the past decade.

Using sector-level IO analysis to calculate embodied emissions from intermediate and final demand jointly is well-suited for assessing environmental impacts of a sector or group of sectors, including indicators such as biodiversity loss[12] and material resource use[13]. In particular, this approach has already been applied to estimate GHG emissions in several contexts. Dente et al. examined the GHG footprint of Japanese material sectors in 2011[14], while Hertwich & Wood analysed global production footprints of five sectors from 1995 to 2015 using EXIOBASE[15]. More recently, Hennequin et al. derived sector-level subnational production footprints for Europe in 2017[16], and Wilting & In't Veld compared consumption- and production-based footprints across European countries leveraging ICIO data[17].

We apply the extended IO analysis to FIGARO data (full international and global accounts for research in IO analysis, 2023 edition) from 2010 to 2021[18] covering 45 countries (27 EU member countries, main EU-trading partners, such as the US and China), a rest-of-the-world aggregate and 64 industries according to the industry classification scheme NACE (Nomenclature statistique des activités économiques dans la Communauté Européenne, 2-digit-level) or aggregates thereof[19]. The NACE 2-digit level provides a broad industry classification, including, for instance, the chemical or automotive industry. We classify three industries as digital industries: hardware (C26), communications (J61), and IT services (J62 & J63) (see Supplementary Notes 1: Digital industry classification). We refer to the remaining 60 industries as non-digital industries. The environmental extension of FIGARO data is also disseminated by Eurostat, which provides estimates of GHG emissions by industry and country expressed in CO2e equivalents (CO2e). Further information on the FIGARO dataset can be found in the Data section.

Moreover, to differentiate embodied emissions of final demand of digital industries from those generated by digital industries as intermediate inputs in non-digital industries, we propose the following definitions:

- The GHG emissions directly generated in industries which supply goods and services (such as metals and chemicals) to other industries are referred to as direct emissions.
- The GHG emissions associated with the final demand of digital industries are referred to as embodied emissions from IT services, communications, and hardware, respectively, or when considered jointly, as embodied emissions from digital industries. Our calculation of embodied emissions encompasses almost all upstream Scope 3 emissions, as well as Scope 1 and Scope 2 emissions of digital industries (for instance, the energy consumed by data centres and mobile operators). We do not include downstream Scope 3 emissions, such as the electricity use of end user devices and emissions from disposal. According to the GHG protocol, Scope 1 emissions are emissions that are owned or controlled by the reporting company, Scope 2 emissions relate to the generation of purchased energy of the reporting company, Scope 3 emissions are emissions that are caused by the activities of the reporting company, but arise from sources not owned or controlled by the company, and can occur upstream or downstream[20,21].
- The embodied GHG emissions of digital technologies embodied in the final demand of non-digital industries are referred to as embodied emissions mediated via other industries. Here, we cannot differentiate between the GHG emissions of the three individual digital industries within this category, as we encounter overlapping digital value chains with respect to the final demand of other industries. For instance, when the automotive industry demands digital hardware, this hardware often includes contributions from IT services, such as software. As a result, the embodied emissions that arise due to hardware usage already integrate the embodied emissions associated with IT services in their supply chain.
- The joint GHG emissions from final demand for digital industries, and from demand for digital industries from non-digital industries, are referred to as embodied emissions of total digital demand. Total digital demand is thus the sum of demand for digital technologies in digital and non-digital industries.

Our results reveal that embodied emissions from total digital demand accounted for 4.1% of global emissions in 2021, up 9.0% since 2010. Looking at drivers of this growth, a key finding of our study is that 42% of direct emissions from digital industries are not transferred to the final demand of digital industries themselves, but instead are accounted for in the embodied emissions of final demand of non-digital industries. The underlying cross-industry use of digital technologies—such as electronics embedded in vehicles and industrial automation systems—is an indication of the increasing structural reliance of the economy on digital technologies. We also show that supply chain-related (upstream Scope 3) emissions of digital industries are much larger than Scope 1 and 2 emissions, aligning with earlier findings of the growing importance of Scope 3 emissions at the economy-wide level[15]. Moreover, we find that a surge in demand for IT services, such as artificial intelligence, is a further substantial driver of digital embodied emissions.

Results

Embodied emissions of total digital demand are increasing, but more slowly than global emissions

Figure 1 illustrates embodied emissions of total digital demand over time, as well as the relative contributions of digital industries to global emissions and economic output. Absolute embodied emissions have risen from 1965 MtCO2e in 2010 to 2141 MtCO2e in 2021, by 9.0%. At the same time, the share of digital industries of the total output of the economy increased from 5.2 to 5.6%. The share of embodied emissions in global GHG emissions, however, declined slightly, from 4.2 to 4.1%. Hence, the global contribution of digital industries to economic output increased, while the contribution to global GHG emissions decreased.

42% of total digital demand's embodied emissions occur within the value chains of non-digital industries, and Scope 3 accounts for the largest share of embodied emissions

Figure 2 illustrates emission flows from industries of origin to final demand, expressed in percentages for the year 2021. The left-hand side shows the industries producing direct emissions in the digital value chain, while the middle section represents embodied emissions within final products or services, distinguishing between emissions embodied in the final demand of the three digital industries (hardware, communication, and IT services) and those embodied in intermediate demand for digital technologies stemming from other industries, such as automotive. The right-hand side attributes emissions to areas of final demand (see Supplementary Table 1 for definitions of the five final demand categories). The analysis shows that 42% of total embodied emissions of digital industries are not transferred via the final demand for digital industries, but instead are transferred via the value chains

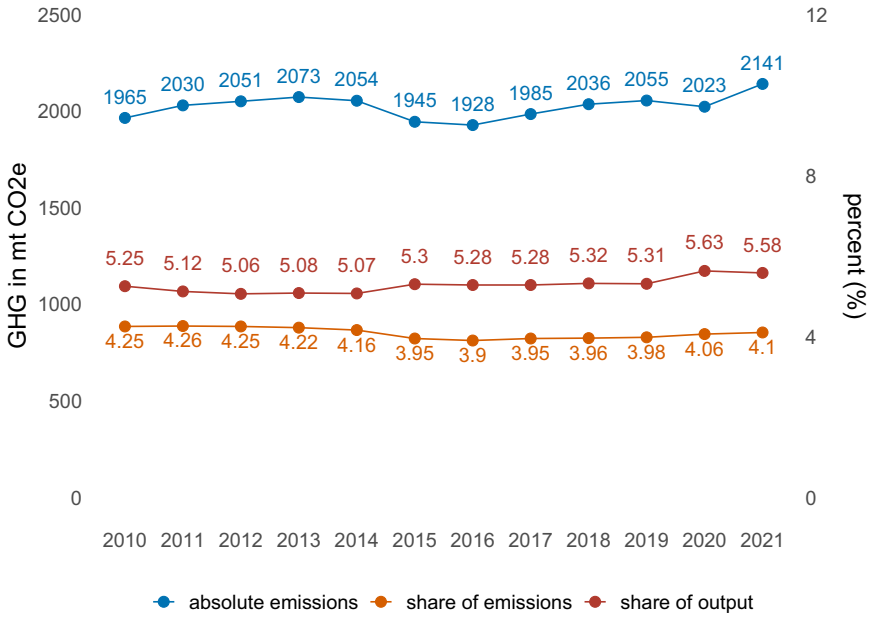

Fig. 1 | Embodied emissions of total digital demand over time. The blue line shows absolute embodied emissions, the orange line shows embodied emissions as a percentage of global greenhouse gas emissions, and the red line shows the output of digital industries as a percentage of total economic output. A deflation procedure was applied to the output data to ensure a consistent and harmonised price system throughout the time series (see Supplementary Notes 1: Estimation of Constant Prices). To check the robustness of our results, we performed an uncertainty analysis (see Supplementary Notes 2).

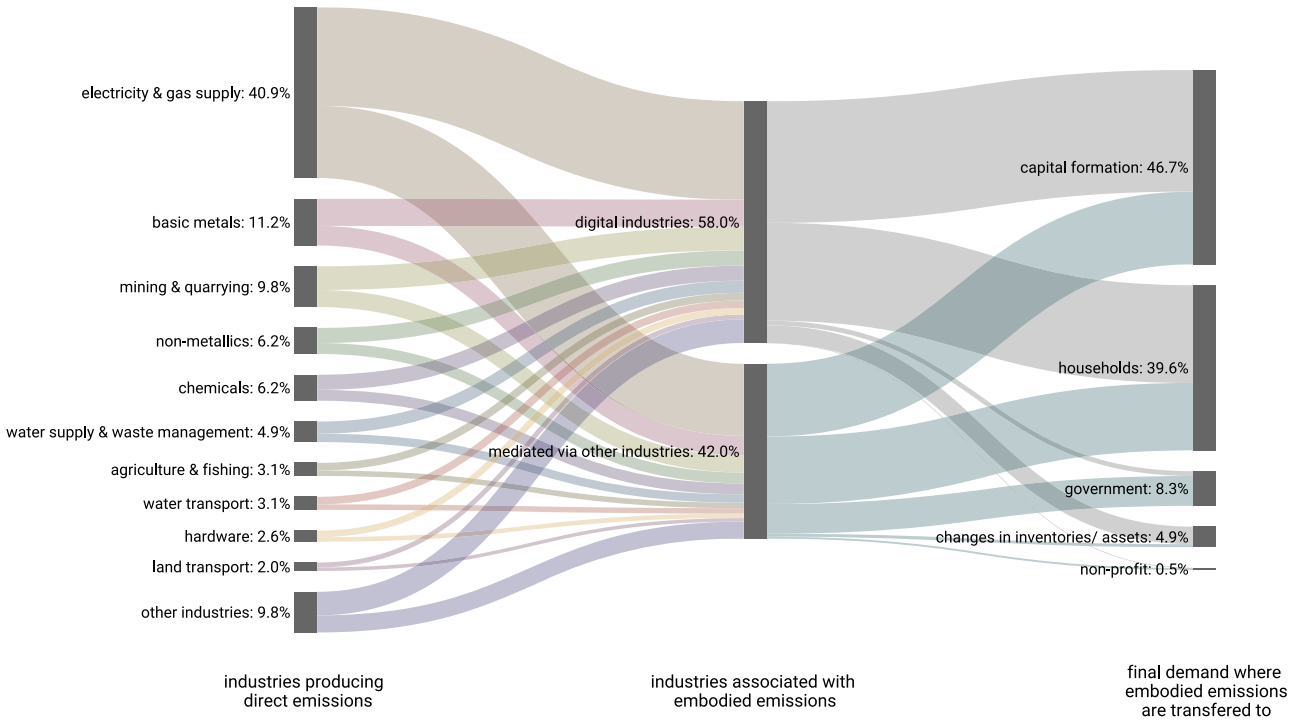

Fig. 2 | Sankey diagram illustrating the greenhouse gas emissions associated with digital industries across different stages of the value chain in 2021. The left-hand side depicts the industries generating direct emissions within the supply chains of digital industries; the middle section illustrates how these direct emissions are either retained within digital industries or passed through to non-digital industries; the right-hand side indicates how embodied emissions are distributed across final demand categories, as defined by the input-output framework. For corresponding results for 2010, see Supplementary Figure 3.

and final demand of non-digital industries. Regarding source industries, electricity and gas supply contribute the largest share of direct emissions (40.9%), followed by basic metals (11.2%), and mining and quarrying (9.8%). Among the final demand categories, capital formation (46.7%) and household consumption (39.6%) are the main destinations for embodied emissions of digital industries.

To further understand emission sources, we analyse their distribution across supply chain stages (see Supplementary Fig. 2 and Supplementary Table 3). The analysis shows that during the production of digital products and services, the majority of emissions —77–87%—occur upstream (Scope 3), as opposed to a smaller share from Scope 1 and 2 emissions.

Most emissions through hardware and digital technology adoption in non-digital industries. IT services on the rise

Figure 3 illustrates embodied emissions over time, categorised into embodied emissions associated with the final demand for hardware, communications, and IT services industries, as well as digital embodied emissions mediated via other industries. Final hardware demand accounted for the

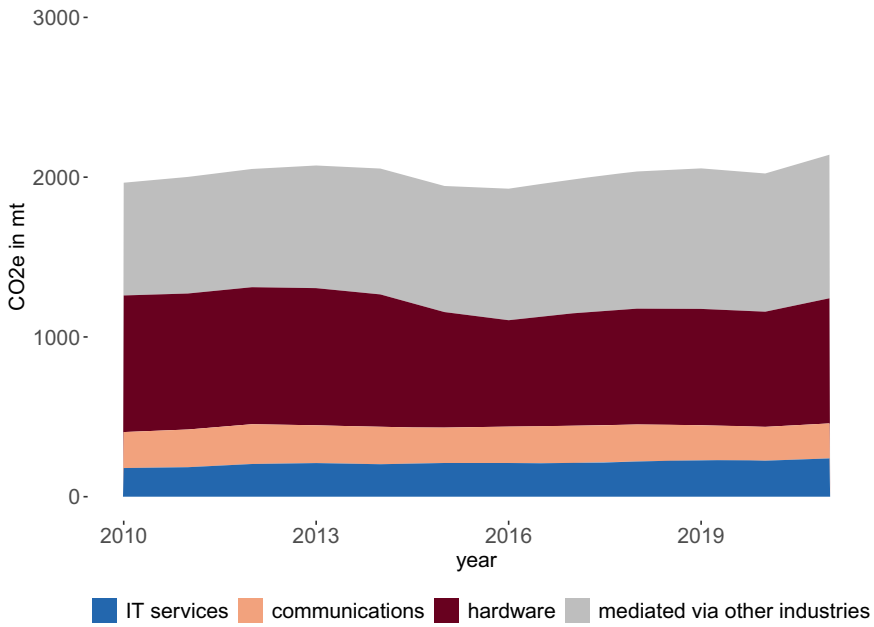

Fig. 3 | Embodied emissions of total digital demand (2010-2021) broken down by industry: hardware (red), communications (apricot), and IT services (blue), as well as embodied emissions mediated via other industries (grey area); See Supplementary Table 2 for values.

largest share of emissions until 2014, after which emissions mediated via other industries became dominant. Throughout the observed period, embodied emissions from the final demand of hardware declined both in absolute and relative terms. Conversely, embodied emissions mediated via other industries increased over the observed period from 35.9 % in 2010 to 42 % of total embodied emissions in 2021. Replicating the same analysis for the three digital industries individually (see Supplementary Table 4), we find that the digital industries driving growth in embodied emissions mediated via other industries are IT services (growing by 61% from 2010 to 2021), and hardware (growing by 30% from 2010 to 2021). This shift indicates that reductions in the embodied emissions of the final demand of hardware are more than outweighed by growth in embodied emissions passed through to non-digital industries—particularly via increasing intermediate hardware and IT service demand. This results in an overall increase in emissions from total digital demand.

Utilising the adjusted Leontief inverse matrix L^{ICT}, defined in Equation (11) (see Methods section), we compute the embodied emissions associated with digital industries as matrix $E^{\mathrm{ICT}} = [c] \cdot L^{ICT} \cdot [y]$, where c denotes the vector of direct GHG emissions intensities and y represents the final demand vector across all sectors (see Equation (12)). Hence, changes in embodied emissions can be attributed to these three analytical components. In Fig. 4, we present a decomposition of the changes in embodied emissions from digital industries over the period 2010-2021. Panel (a) displays the overall time trend in ICT-related embodied emissions by industry. Panels (b) to (d) disentangle the contributions of each component to the overall trend: direct emissions intensities (c), inter-industry linkages captured by the adjusted Leontief inverse (L^{ICT}), and final demand (y). The c and L^{ICT} values are weighted by their relative importance in order to accurately reflect their actual contributions.

Panel (a) shows that emissions from IT services and those mediated via other industries increased more rapidly than global emissions, while emissions from hardware and communications declined in absolute terms and relative to the economy-wide average. Panel (b) reveals a decline in average upstream GHG emission intensity across all digital sectors, with reductions in all categories surpassing the economy-wide average—except for communications. Panel (c) demonstrates a near 50% increase in Leontief weights associated with digital demand mediated via non-digital industries. This implies a growing structural reliance of other sectors on digital inputs to produce one unit of economic output. In other words, the amount of input from digital industries necessary to generate one unit of value in non-digital industries increased substantially over the observed period. This resulted in an above-average rise in digital emissions mediated via other industries. Panel (d) shows that final demand increased across all digital industries between 2010 and 2021. Notably, demand for IT services more than doubled. This leads to the conclusion that despite concurrent declines in both Leontief weights and upstream emission intensity for IT services, these reductions were insufficient to offset the surge in demand. As a result, the embodied emissions associated with IT services grew at a rate that exceeded the economy-wide average.

US and Europe import digital emissions; China exports, but also increasingly consumes domestically

Figure 5 illustrates the flow of digital embodied emissions across regions, from the region where direct emissions are being produced, over the region of the industry serving final demand to the region of final consumption, expressed in percent for 2021. The figure reveals geographical differences between directly produced and consumed emissions (left- and right-hand side).

China has emerged as both the largest producer and net exporter of embodied emissions within digital value chains. The left-hand side reveals that China is the largest contributor of direct emissions (48.8%). The middle shows that most emissions remain in China for further processing. Comparing 2010 and 2021 (see Supplementary Fig. 4), China's share of global embodied emissions in digital industries increased by 10 percentage points (from 37.5 to 47.7%), underscoring its growing importance in manufacturing hardware and providing IT services. The right-hand side shows that in 2021, China accounted for 30% of embodied emissions from total digital demand from a consumption perspective, substantially less than from a production perspective. Nonetheless, from a consumption perspective, China's share of embodied emissions also rose substantially (by approximately 50% between 2010 and 2021), highlighting the country's growing relevance in digital emissions from this angle as well. Looking at other regions, Europe and the United States together accounted for 12% of emissions from a production perspective, but double the amount (25%) from a consumption perspective, revealing that these regions are net importers of emissions. Our findings thereby point to the relevance of considering consumption-based perspectives in global emissions accounting and mitigation strategies[22].

For an additional discussion of regional differences, see Supplementary Table 5 and Supplementary Table 6.

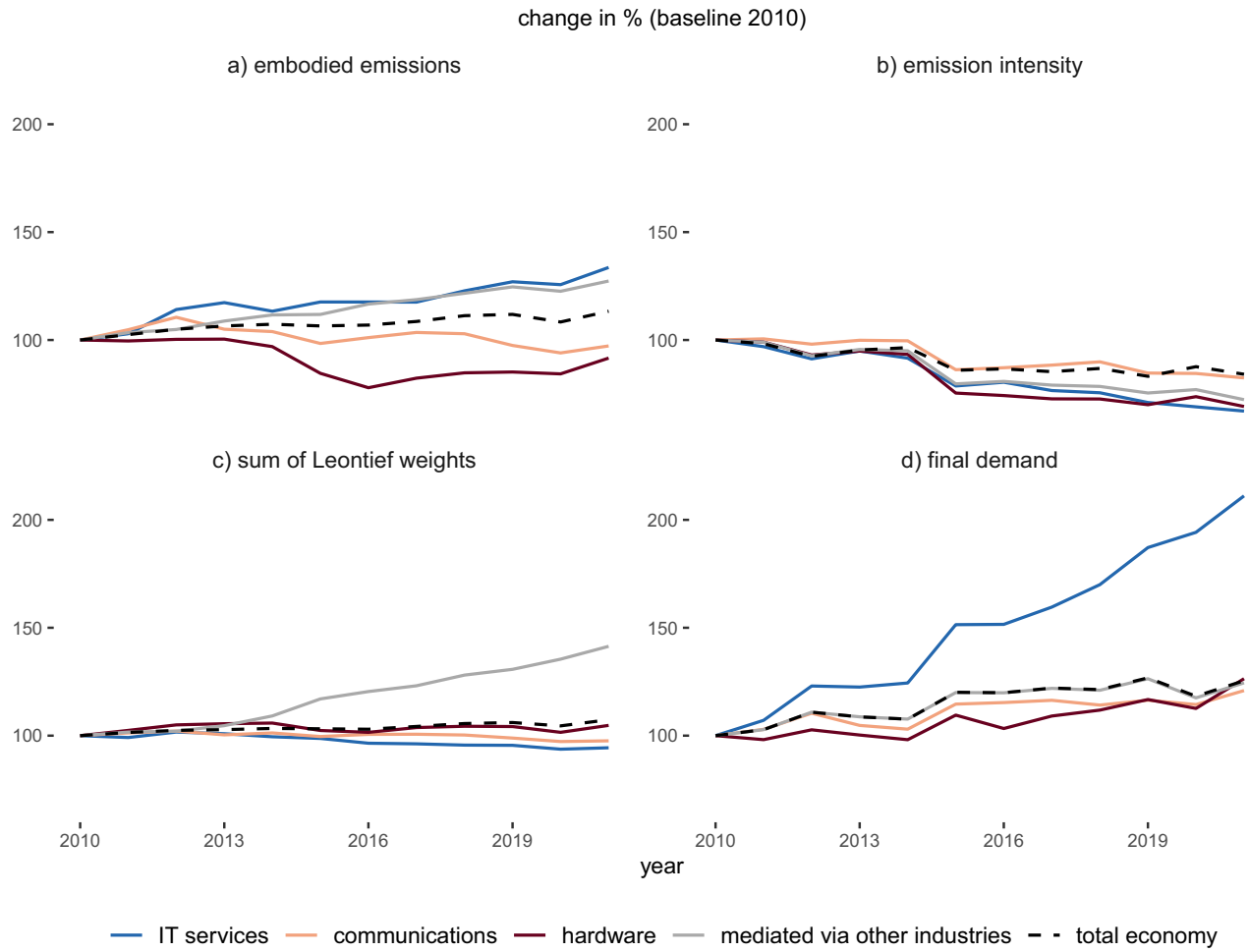

Fig. 4 | Decomposition of relative changes in embodied emissions for three digital industries (IT services (blue), communications (yellow), hardware (red)) and emissions mediated via other industries (grey). The baseline is 100 %, all monetary values are deflated (see Supplementary Notes 1: Estimation of Constant Prices for details). **a** Embodied emissions. **b** Average upstream greenhouse gas emission intensity weighted by demand (direct emission intensity in input industries). **c** Average sum of Leontief weights weighted by final demand. **d** Final demand in deflated monetary terms.

Discussion

Our results underscore the importance of accounting for Scope 3 upstream emissions generated in the supply chain of digital and non-digital industries by digital inputs. Conceptually, Van Oorschot et al. identify three fields of action for each part of a value chain to reduce its overall environmental footprint: minimising the direct local impacts of production processes, improving the efficiency of material inputs, and guiding procurement towards sustainable suppliers[23]. To address the supply chain-related emissions practically, policymakers should increasingly implement measures that hold firms accountable for Scope 3 embodied emissions. Scope 3 reporting—as required under the European Sustainability Reporting Standards since 2024[24]—should become mandatory globally and be accompanied by ambitious emissions reduction targets. Given the significance of sectoral indirect emissions, a universal and harmonised carbon accounting framework is essential. For instance, identifying high- and low-performing firms along their supply chains at the micro level enables more effective policy targeting. Moreover, systematically displaying accurate carbon performance and other environmental information on each product or service can empower consumers to shift demand towards more sustainable options. This goal is beyond reach with the current practices of the GHG Protocol, but recent research has shown that reporting could be improved by applying a distributed IO approach at the levels of companies[25,26]. Also, the European Commission's concept of a digital product passport, which is to be implemented for various product groups in the next years as part of the Ecodesign for Sustainable Products Regulation, could be a useful tool to enhance transparency about regulatory compliance and environmental impacts of products[27].

Examining sources of emissions, hardware remains the most important source of embodied emissions among the three digital industries, reflecting energy-intensive processes in the production of integrated circuits and emission-intensive raw material production[28,29]. This aligns with previous studies showing that most emissions of digital technologies are embodied manufacturing emissions[30,31] (except for some cases, e.g. for TV devices with relatively long use phases (7 years)[32]). To address hardware manufacturing emissions, policies should incentivise circularity-oriented, modular design, as well as the use of recycled and recyclable materials among manufacturers[33–35]. By extending hardware use (and reuse) phases, increasing repairability, and fostering the use of refurbished hardware, the demand for, and thus the upstream emissions of, hardware could be reduced whilst creating new business opportunities, e.g. in the field of product-service-systems[36].

By contrast, IT services represent a smaller share of emissions but show the highest growth rates up to 2021. Due to the time lag in publishing IO data, our analysis does not capture recent surges in energy consumption within IT services, driven by the rapid rise of generative artificial intelligence, starting at the end of 2022 with the introduction of ChatGPT and other large-scale AI models[37]. Nevertheless, while the rapid expansion of technologies such as AI and big data may introduce new dynamics, most industrial systems (including the ICT sector) exhibit considerable inertia due to path dependencies, capital stock lifetimes, and long-term

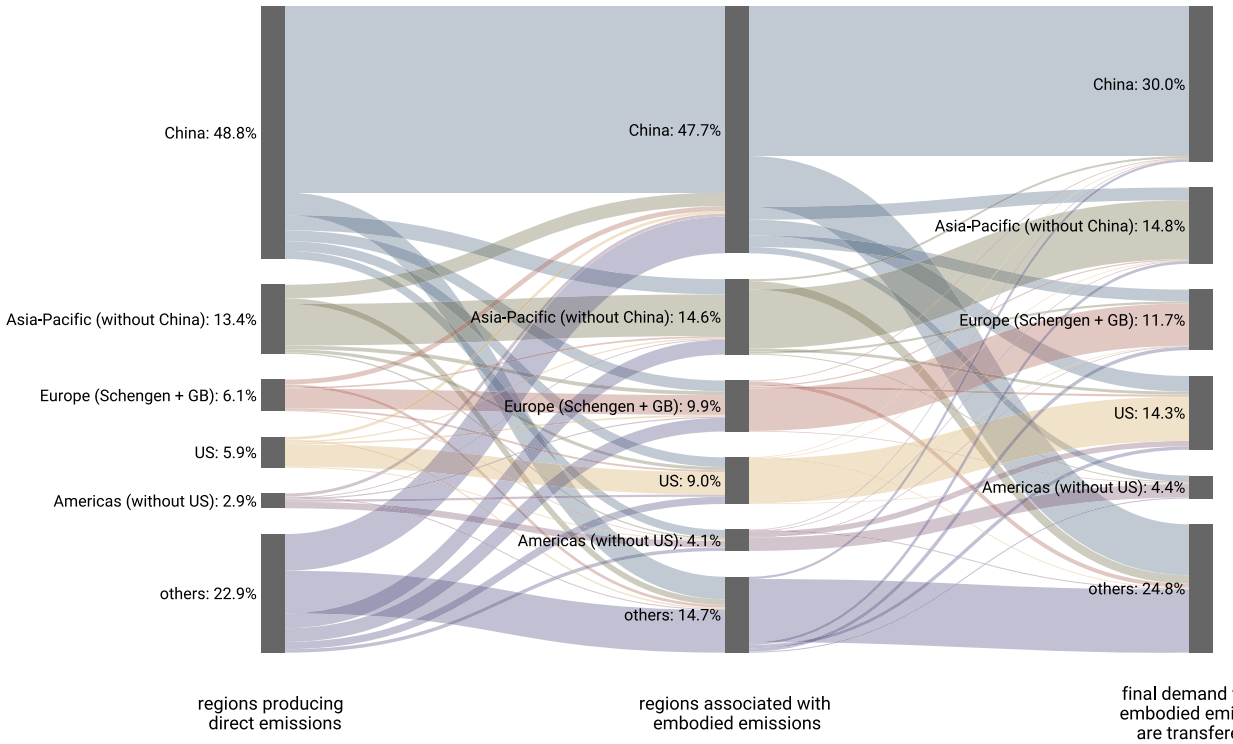

Fig. 5 | Sankey diagram showing digital industries' greenhouse gas emissions at different stages of the value chains of digital industries in 2021. The left-hand side shows the country of origin of direct emissions (production perspective), the centre shows countries where final products with embodied emissions are being produced, and the right-hand side indicates where these emissions are ultimately consumed (consumption perspective). For corresponding results for 2010, see Supplementary Fig. 4.

infrastructure investments. As such, many factors are unlikely to shift substantially in the short term. Even so, combining the surge in AI adoption with the already strong upward trajectory of emissions from IT services, our results suggest that IT services may soon become a more relevant driver of emissions within the digital economy[38–40]. To limit growth in embodied emissions, IT services, such as websites, applications, and AI tools, should be designed according to Green IT principles, reducing their hardware, network and data centre service demand, creating resource-efficient software, and choosing the most resource-saving solution for any given IT challenge (sufficiency-oriented approach)[41–43].

Comparing the geographical distribution of emissions of digital industries, China dominates digital industry emissions across all stages of the supply chain. In 2021, it accounted for almost 50% of emissions embodied in digital product and service manufacturing and provision, a substantial share of which was effectively exported to other countries. This mismatch between production and consumption highlights the limitations of current carbon accounting systems that rely on production-based metrics. Extending consumption-based adjustments, such as those proposed under the EU Carbon Border Adjustment Mechanism (CBAM), to further sectors of the economy, as well as additional processing stages of products, may be necessary to ensure equitable climate accountability for internationally traded digital goods[44,45]. As digital technologies are primarily positioned at the end of the value chain, they are currently not included in the CBAM list of goods (Annex 1 of [44]). There may be a leakage effect by incentivising domestic producers not to import CBAM-regulated raw materials but instead import unregulated (processed) inputs. Therefore, including processed goods and services into the CBAM, while considering their actual embodied emissions, could reduce adverse incentivization for companies and maximise the global GHG reduction potential[45],? Strengthening international cooperation—particularly with China—will also be essential for regulating emissions along global (digital) supply chains[45,46].

Our study has several limitations. First, it excludes direct use-phase emissions from private end-user devices (e.g. home laptop electricity use) as well as emissions from the end-of-life phase (e.g. emissions of dismantling hardware). Including use-phase emissions alone using estimated figures for 2020 reported in Table B.5 Supplementary Material of Freitag et al.[7], could raise our 2020 total emission estimate by a bit more than 20% (additional 440 Mt added to 2023 Mt). Second, our industry classification relies on the NACE 2-digit level, limiting resolution. In contrast to some previous studies (e.g. [32,47,48]), we adopt a broader definition of digital industries to include embedded connectivity (smart speakers, smart watches) and the industrial Internet-of-Things (sensors and chips as inputs in the automotive industry). On the other hand, we exclude some industries that are only available at the NACE 3-digit level, such as software publishing. The NACE 3-digit level offers a more detailed categorisation of industries than the NACE 2-digit division, further subdividing the latter into 272 groups that specify distinct types of activities. The Supplementary Notes 1 'Digital industry classification' outlines the industries we included and excluded in our analysis. Third, our analysis focuses solely on GHG emissions. However, digital systems also have substantial water, material, and e-waste footprints, which warrant more comprehensive environmental assessments.

Future research should aim to combine GHG emissions data with other environmental indicators, such as material flows[49], water and land use[50]. It could explore hybrid IO and life-cycle approaches to include use-phase and indirect environmental impacts, such as changing use patterns of digital technologies and rebound effects[51]. Further, modelling capital stocks and capital formation endogenously[52] in the context of digital infrastructure investment could improve the understanding of the explanatory variables behind emissions trends and enhance the understanding of decarbonisation levers with respect to the digital transformation. Lastly, the quantification of downstream effects of the digital transformation deserves further attention. These effects include potential mitigation co-benefits, such as grid and demand side management for the improved integration of renewable energies, as well as risks, such as an increased demand and resource use stimulated by digitalisation-related efficiency improvements.

Methods

Our analysis combines IO tables with industry-level GHG emissions data to estimate the embodied emissions of digital industries. We use the Leontief inverse[53] as our core analytical framework, extending it to account for embodied emissions of one industry embedded in the final demand of another industry, i.e. digital embodied emissions embedded in the final demand of non-digital industries. We call these emissions 'emissions mediated via other industries'.

In the following, we outline the standard Leontief approach, describe our methodological extensions and present the data sources used.

Derivation of the standard Leontief inverse to calculate emissions embodied in final demand

The Leontief inverse is derived as follows. In an IO model, all products and services produced by an economy's n industries are denoted by the vector $\mathbf{x}$ (total output). A is the technological coefficient matrix: each column shows the immediate direct input that one industry receives from all other industries to produce one unit of output in monetary terms. Final demand is denoted by the vector $\mathbf{y}$. Hence, the basic equation of an IO model is given by:

$$\mathbf{x} = A \cdot \mathbf{x} + \mathbf{y}. \tag{1}$$

Rearranging the equation allows to express total output as a function of final demand (where I is the identity matrix):

$$\mathbf{x} = (I - A)^{-1} \cdot \mathbf{y}. \tag{2}$$

The Leontief inverse, L, is then given by:

$$L = (I - A)^{-1}. \tag{3}$$

The intuition of the Leontief inverse is that each column shows the immediate direct as well as indirect input one industry receives from all industries to produce one unit of final demand. Indirect inputs are prior inputs needed by suppliers to produce inputs that are used by the industries of interest.

By accounting for indirect inputs, the Leontief approach enables the estimation of industries' embodied emissions. With respect to final demand, the embodied emissions E can be calculated as follows. Let $\mathbf{c} = (\ldots, c_i, \ldots)$ denote the row vector of direct GHG emissions (i.e. Scope 1 emissions) per unit of output for each industry. To compute the total GHG emissions associated with final demand, define $[y]$ as the diagonal matrix derived from the final demand vector $\mathbf{y}$, and $[c]$ as the diagonal matrix representation of $\mathbf{c}$. The resulting matrix is:

$$E = [c] \cdot L \cdot [y] = \left[c_i \cdot l_{ij} \cdot y_j\right] \tag{4}$$

This matrix decomposes the total GHG emissions into the elementary contributions $c_i \cdot l_{ij} \cdot y_j$, corresponding to the GHG emissions of industry i to serve the final demand of industry j. This is a classification of emissions by origin and destination. The sum of row i adds up to the emissions of industry i, while the sum of column j adds up to the embodied emissions of the final demand of industry j, and the sum of all the coefficients adds up to the total GHG emissions of the economy. In the standard Leontief approach, the matrix L incorporates the contributions of the entire economy, no matter whether they relate to digital technologies or not.

In the following, we model the ICT sector as an aggregation of several individual sectors ($i,\ldots,m$). For simplicity, we consider them in contiguous order. Note that although our reasoning is applied here to the ICT sector, it can be extended to any group of individual sectors. The embodied emissions of the final demand of the ICT sector, denoted by F^{ICT}, are the scalar value obtained by aggregating the sums of the columns $i,\ldots,m$ in matrix E. The value can be obtained by considering the ICT's sector final demand vector $\mathbf{y}^{\mathrm{ICT}}$, constructed by zeroing all elements in the final demand vector y except those corresponding to digital industries.

$$F^{\mathrm{ICT}} = \mathbf{c} \cdot L \cdot \mathbf{y}^{\mathrm{ICT}} \tag{5}$$

Methodological extension of the standard Leontief approach: Measuring embodied emissions of digital technologies embedded in the final demand of non-digital industries

The Leontief framework, as described above, only allows for the calculation of embodied emissions associated with the final demand of an industry. This property implies that digital technologies produced as inputs for the final demand of other industries are not included in the standard Leontief framework. This issue is best illustrated by the following example: if the final demand of an industry is zero and the output of that industry is used exclusively as an input for other industries, no emissions are attributed to that industry in the standard Leontief framework.

However, a large amount of digital technology is now integrated into household appliances, consumer goods, automobiles or industrial machines. For example, household appliances such as refrigerators and lawnmowers increasingly incorporate connected components. Thus, digital technologies are often only one part of a product, i.e. intermediate input for other industries. Moreover, industries increasingly rely on information technology infrastructure to produce and deliver their products. This reliance is also part of the ICT embodied footprint. However, the standard Leontief framework does not allow for considering embodied emissions that are part of the value chain of other non-digital industries' final demand. Likewise, previous standardisations efforts such as the ITU-T recommendation L.1450 treat the issue of embedded connectivity as an area of future concern, given the difficulties in measuring related emissions[54].

We therefore introduce the concept of emissions mediated via other industries. To further illustrate the concept, imagine the example of electronics in cars. Digital devices are becoming increasingly relevant components of car manufacturing due to increasing demands for entertainment (e.g. touch screens), safety (e.g. cameras for collision avoidance systems) and connectivity (e.g. WiFi and cellular connections). Each electronic module includes numerous parts, such as sensors, cables, and chips. Depending on the car model, the total amount can be several hundreds or thousands chips, approximately 2000 chips reported by the Financial Times for electric cars. In consequence, increasingly digitalised cars require growing amounts of intermediate digital components, and emissions embodied in digital technologies could be increasingly mediated via other industries, such as the automotive industry, to final demand.

In order to gain insight into the magnitude of GHG emissions from digital technologies being intermediate input for other industries, we extend the Leontief framework to take into account emissions mediated via other industries.

To adjust for intermediate demand, we assume that the combination of inputs required to produce one unit of a good or service for final demand is identical to the combination used to produce the good or service for intermediate demand. This assumption implies that, on average, the same ratios of inputs, such as plastic and metals, are needed to produce digital goods, regardless of the purpose. Thus, we can take the column vector l_i of the digital industry i from the Leontief inverse L and scale it to fit the column vector of industry j, as illustrated in Fig. 6. To do this, we need to multiply l_i by the ratio of how much of industry i is needed by industry j relative to that required by industry i itself. For example, if we need one unit of industry i to produce one unit of industry i, but only 0.5 units from industry i for industry j, we also need 0.5 times less from all other industries to produce i for the final demand of industry j. Equation (6) formalises the calculation of the intermediate input from industry i embedded in the Leontief inverse vector of industry j.

$$l_j^i = \frac{l_{i,j}}{l_{i,i}} \cdot l_i. \tag{6}$$

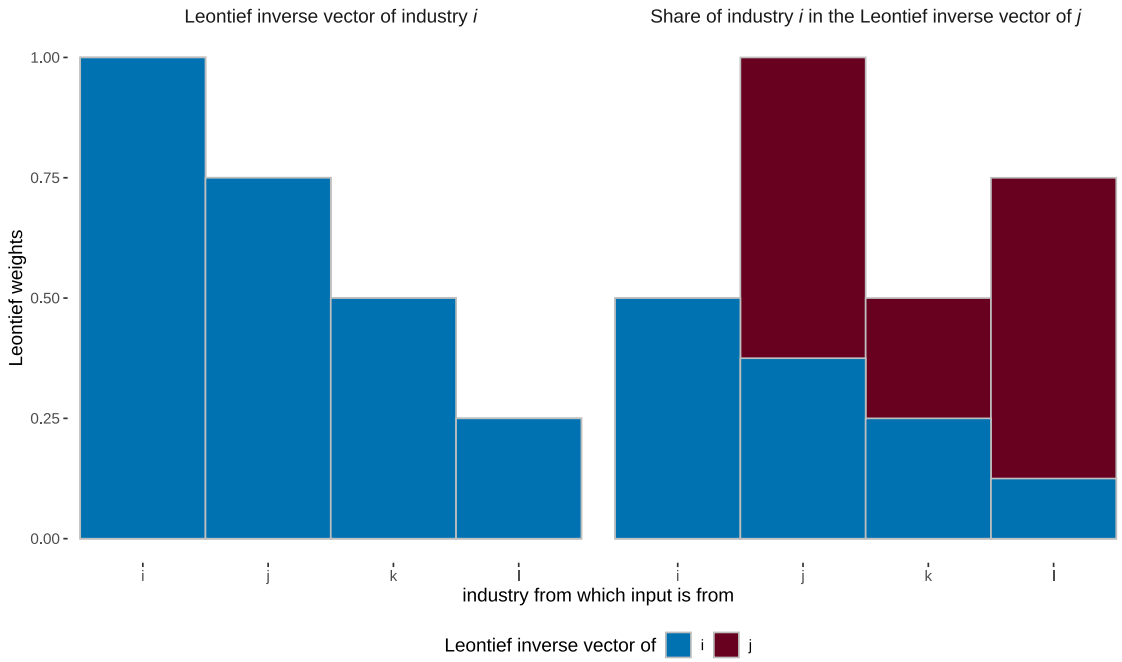

Fig. 6 | Illustration of the intermediate input of industry *i* in the Leontief column of industry *j*. The left blue bars represent the values of the column vector l_i of the Leontief inverse matrix *L*, in decreasing order. The right blue and red bars represent the values of the column vector l_j of industry *j*. The blue part represents the productions by all industries required by *i* to serve *j*. It is a version of the blue part on the left-hand side, scaled by a factor 0.5 ($l_{i,j}/l_{i,i}$). The red part represents the remaining productions that do not involve industry *i*.

To calculate the intermediate inputs of industry *i* in all industries, we express Equation (6) in matrix form:

$$L^i = \frac{1}{l_{i,i}} \cdot L_{*,i} \cdot L_{i,*}. \tag{7}$$

The output is an adjusted Leontief inverse, L^i, for industry *i*, where l^i_i shows the direct and indirect inputs that industry *i* receives from all industries in order to produce one unit of final demand. The other columns, $l^i_j, l^i_k, \ldots$, show the direct and indirect inputs that industry *i* receives from all industries in order to produce the amount necessary to meet the final demand of all industries except *i* (see Equation (8)). Hence, in this paper, we adjust the Leontief inverse to contain only the contributions that require ICT production, at any step of the value chain.

$$L^i = \begin{bmatrix} l^i_{ii} & l^i_{ij} & l^i_{ik} & \cdots \\ l^i_{ji} & l^i_{jj} & l^i_{jk} & \cdots \\ l^i_{ki} & l^i_{kj} & l^i_{kk} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix} \tag{8}$$

Inputs to produce *i* for its final demand

Inputs to produce *i* for final demand of $j \neq i$

To calculate the total intermediate footprint including all digital industries, we have to add up several intermediate inputs from different industries (and countries), for instance, from several software and hardware industries. This is not trivial, as double-counting is a serious problem that occurs when simply adding up all intermediate inputs. For example, when calculating the intermediate input of the software industry in the automobile industry, the emissions embodied in the hardware on which the software runs are already included in the embodied emissions of the software industry. Therefore, if one wants to calculate the joint share of intermediate inputs of two industries in the Leontief column of a third industry, one has to take into account that embodied emissions can be attributed to two different industries if they are in the same value chain. To solve this problem, we subtract the intermediate inputs of industry *i* from the Leontief inverse as follows:

$$L^{-i} = L - L^i. \tag{9}$$

Then, we add the intermediate inputs of industry *k*, which are not included in L^i, to the elements of L^i. This is done by replacing *L* with L^{-i} and *i* with *k* in Equation (7).

$$L^{i,k} = L^i + \frac{1}{l^{-i}_{k,k}} \cdot L^{-i}_{*,k} \cdot L^{-i}_{k,*}. \tag{10}$$

Matrix $L^{i,k}$ now contains the inputs of all industries that the industries *i* and *k* require to produce input for one unit of industry *j*.

To add up the intermediate input of all digital industries *i*,..., *m*, we iterate the procedure defined by Eqs. (9) and (10) up to industry *m*:

$$L^{ICT} = L^{i,\ldots,m} = L^i + \cdots + \frac{1}{l^{-i,\ldots,-m-1}_{m,m}} \cdot L^{-i,\ldots,-m-1}_{*,m} \cdot L^{-i,\ldots,-m-1}_{m,*}. \tag{11}$$

Moreover, we can verify that adding up all intermediate inputs from all industries of the economy to industry *j* equals the Leontief column of industry *j*, i.e. $l^{1,\ldots,n}_j = l_j$. In other words, a Leontief column is the sum of all intermediate inputs corrected for double counting. One can simply verify this property by showing that $L^{1,\ldots,n} - L = 0$.

Finally, total embodied emissions of all digital industries E^{ICT}, including intermediate demand in non-digital industries, are fully accounted for in the following matrix:

$$E^{\mathrm{ICT}} = [c] \cdot L^{i,\ldots,m} \cdot [y] = \left[c_i \cdot l^{i,\ldots,m}_{ij} \cdot y_j\right] \tag{12}$$

This matrix is analogous to matrix E of Eq. (4), with the Leontief inverse L replaced by the ICT-adjusted Leontief inverse $L^{i,\ldots,m}$. This new matrix, denoted by E^{ICT}, decomposes the ICT total embodied emissions into elementary contributions of the form $c_i\, l_{ij}^{i,\ldots,m}\, y_j$ representing the emissions of the i-th sector that are required by the ICT industry to satisfy the final demand y_j of the j-th sector. The sum of row i adds up to the direct emissions of industry i required for its production, while the sum of column j adds up to the embodied emissions of ICT production required by the final demand of industry j, and the sum of all the coefficients adds up to the total embodied emissions T^{ICT}, which are always larger than (or can in theory be equal to) F^{ICT}. Using the ICT-adjusted Leontief inverse, we obtain T^{ICT} as:

$$T^{\mathrm{ICT}} = \mathbf{c} \cdot L^{i,\ldots,m} \cdot \mathbf{y} \tag{13}$$

Additionally, industries can be aggregated by simply aggregating the row sums for the contributing emissions, or by simply aggregating column sums for the final demand's embodied emissions to conveniently present results such as Sankey diagrams. For instance, $T^{\mathrm{ICT}} - F^{\mathrm{ICT}}$ represents 42% of the total embodied emissions of ICT, which are contained in the final demand of all non-digital industries. Moreover, with the full matrix E^{ICT}, we are able to analyse the embodied emissions of non-digital industries at a granular, sector-by-sector level.

Our approach leads numerically to the same results as the method of Cabernard et al., which decomposes the total embodied emissions of an arbitrary group of sectors—referred to as 'target sectors' in their paper—into a matrix structure similar to our matrix E^{ICT}[13]. However, we introduce the concept of an adjusted Leontief inverse $L^{i,\ldots,m}$, which is a reduction of the standard Leontief inverse L, designed for the analysis of target sectors (in our case, the ICT sector). Our alternative algorithm has several advantages. For instance, it does not require partitioning the economy into target sectors and the rest of the economy. Moreover, it is particularly well suited for a group of target sectors consisting of a relatively small number of individual industries (as it is the case for the ICT sector) since the proposed approach involves only a limited number of additional computations beyond the calculation of the standard Leontief inverse. Furthermore, the iterative nature of our algorithm allows intermediate embodied emissions from several industries to be aggregated or disaggregated, thereby providing novel insights into the interconnectedness of global value chains.

Also, the advantages of IO analysis over bottom-up approaches include the availability of annually updated, open-access data, which facilitates the analysis of trends over multiple years. Another strength is that the approach attempts to model the technical processes involved in specific products and industries, allowing to comprehensively capturing value chains over the analysed period.

Data

We use FIGARO (Full international and global accounts for research in IO(?)) tables (2023 edition), Eurostat's annual IO tables covering 64 industries (NACE, rev.2, two digits), 45 countries, including 27 EU member countries, several non-member countries and a rest-of-the-world aggregate (ROW). Moreover, FIGARO distinguishes between five categories of final demand: capital formation, households, government, changes in inventories/assets, and non-profit (see Supplementary Table 1).

FIGARO is an environmentally-extended IO database as it provides air emissions as environmental extensions to the IO trade data(?). The data is derived from air emissions accounts reported by the EU27, Norway, Switzerland, Turkey, UK's Office for National Statistics, and estimates of air emissions by EUROSTAT based on the EDGAR database for the remaining countries.

The data is available for the period between 2010 and 2021. We use the 2023 edition and not the 2024 edition for the main analysis due to methodologies irregularities in the more current version, which are reported by Eurostat (conversation with Eurostat). Also, we currently cannot use the 2025 edition as the matching environmental information has not published yet.

We chose FIGARO primarily because of its recency, higher industry granularity, and reliability. For example, the latest OECD ICIO data extends only to 2020 and aggregates industries into fewer categories, whereas FIGARO offers more detailed sectoral resolution[55]. FIGARO is also widely used by national statistical offices (e.g. in France and the UK) to calculate consumption-based footprints and is considered in the literature as one of the more robust and reliable multi-regional IO tables.

For a comprehensive description of the data, we refer to Remond-Tiedrez & Rueda-Cantuche[56].

Data availability

The input-output data used in this analysis is the 2023 edition of the FIGARO data. As a more recent version of the data has been published in the meanwhile, the 2023 edition must be requested from Eurostat (`ESTAT-IGA@ec.europa.eu`). The latest version of FIGARO data can be accessed at the European Commission's Eurostat database: https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/database). The data used to calculate deflator is sourced from the 2024 edition of the UN National Accounts Main Aggregates Database, available at: https://unstats.un.org/unsd/snaama/.

Code availability

The code can be accessed via https://github.com/jax90/i-o-tables.

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Janna Axenbeck contributed to conceptualisation, methodology, software, formal analysis, data curation, validation, writing the original draft, review and editing, visualisation, and project administration. Stefanie Kunkel contributed to conceptualisation, writing the original draft, review and editing, visualisation, and project administration. Francis Charpentier contributed to formal analysis, validation, and review and editing. Joris Blain contributed to software, formal analysis, data curation, validation, writing the original draft, review and editing, and visualisation.

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