Supplementary Information: Global Embodied Emissions of Digital Technologies: The Hidden 42 %

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Supplementary Notes 1

Categories of final Demand

Supplementary Table 1. Final demand categories

Final demand category	Description
capital formation	Investment in physical assets like machinery, buildings, etc.
households	Expenditures by households on goods and services.
government	Government expenditures on goods and services.
changes in inventories/ assets	Difference between the stock of goods and services at the beginning and the end of a period.
non-profit	Expenditures by non-profit organizations for goods and services.

Digital industry classification

We define the digital industries based on the available 2-digit NACE industry codes. Our digital industry classification includes Manufacture of computer, electronic, and optical products (C26), Telecommunications (J61), Computer programming, consultancy, and related activities (J62), Information service activities (J63). Thus, in contrast to (1), who use a more granular measurement approach of digital industries, we additionally include the following industries as part of digital industries: Manufacture of instruments and appliances for measuring, testing and navigation; watches and clocks (C26.5); Manufacture of irradiation, electromedical and electrotherapeutic equipment (C26.6); manufacture of optical instruments and photographic equipment (C26.7); Other information service activities (incl. news agency activities and other information service actitivities n.e.c.) (J63.9). In contrast to (1) , we do not include the following sectors: Wholesale of information and communication equipment (G46.5); Software publishing (J58.2), Repair of computers and and communication equipment (S95.1). It should be noted that some studies also include the media and content (MC) industries as part of ICT, MC sectors mainly include Publishing activities (J58), and Motion picture, video and television program production, sound recording and music publishing activities; programming (J59–J60) (2).

Estimation of Constant Prices: The Double Deflation Method

The double deflation method is a widely established approach for deflating current price supply and use tables (SUTs) and input-output tables (IOTs). While the heuristic approach of (3) is considered superior, it requires extensive data that, as far as we are aware, is not available for multi-regional input-output tables (MRIOTs) like FIGARO. The construction of a FIGARO version with constant prices represents a contribution to the literature, as FIGARO, to the best of our knowledge, has not yet been deflated. Given the available data, double deflation remains the most appropriate method.

In double deflation, the sales and purchases specified in IOTs enable the deflation of each product separately within the use part of the tables.

The method applies industry- and country-specific price indexes to corresponding product sales. It implies that both intermediate transactions matrix and final demand vector are deflated row-wise, directly impacting the production volume and that value-added is obtained by deduction. This approach assumes that the price evolution of a product is uniform across all uses (e.g., intermediate consumption, gross fixed capital formation, or final consumption). A detailed discussion of the

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procedure, its implications, and limitations can be found in (4), Chapter 4, Section 4.8. A recent application to the United Kingdom's national accounts by (5) provides further support for double deflation.

Practical Implementation

The double deflation procedure involves two steps. First, diagonalized price indexes are pre-multiplied with intermediate flows, final demand, and gross output by product. Second, deflated value-added is derived by subtracting deflated intermediate inputs from deflated gross output for each product. However, for the purpose of our analysis, only the first step is relevant, as we are primarily concerned with the deflated values of the transaction flow matrix. Nonetheless, we will describe the entire procedure for completeness.

Let π_j^t represent the price index of product j in period t, expressed relative to the base year r, such that $\pi_j^r = 1$. Define $\hat{\pi}^t$ as the diagonal matrix of product price indexes for period t. Let Z denote the transaction flow matrix of intermediate consumption, with n industries i (columns) and products j (rows). In a first step, let $\bar{Z}$, $\bar{\mathbf{x}}$, and $\bar{\mathbf{y}}$ be the deflated transaction flow matrix, deflated gross production, and deflated final demand, respectively.

$$\bar{Z}^t = \left(\hat{\pi}^t\right)^{-1} \cdot Z^t \tag{1}$$

$$\bar{\mathbf{x}}^t = \left(\hat{\pi}^t\right)^{-1} \cdot \mathbf{x}^t \tag{2}$$

$$\bar{\mathbf{y}}^t = \left(\hat{\pi}^t\right)^{-1} \cdot \mathbf{y}^t \tag{3}$$

Second, using the equality between total outputs (rows) and total inputs (columns), the deflated value-added (VA) can then calculated as:

$$\bar{\mathrm{V}}\mathrm{A}^t = \bar{\mathbf{x}}^t - \begin{bmatrix} 1 & \cdots & 1 \end{bmatrix} \cdot \bar{Z}^t \tag{4}$$

Data Sources

Data primarily originates from the National Account Main Aggregates Database (6), as recommended by (7). This database provides extensive geographic coverage and a well-defined sectoral breakdown (approximately 25 sectors, depending on the country). Complementary producer price data are gathered from Eurostat (8), the US Bureau of Labor Statistics (9) and the National Bureau of Statistics of China (10).

Price indexes for the rest of the world in FIGARO are computed as an arithmetic mean of available indexes from non-modeled countries. Missing values, such as those for Russia prior to 2014 or Argentina and Saudi Arabia, are imputed. When extending or reconstructing time series, the growth rate of the closest available (aggregated sector or the rest of the world) price index for the considered time period is applied to maintain consistency across the dataset.

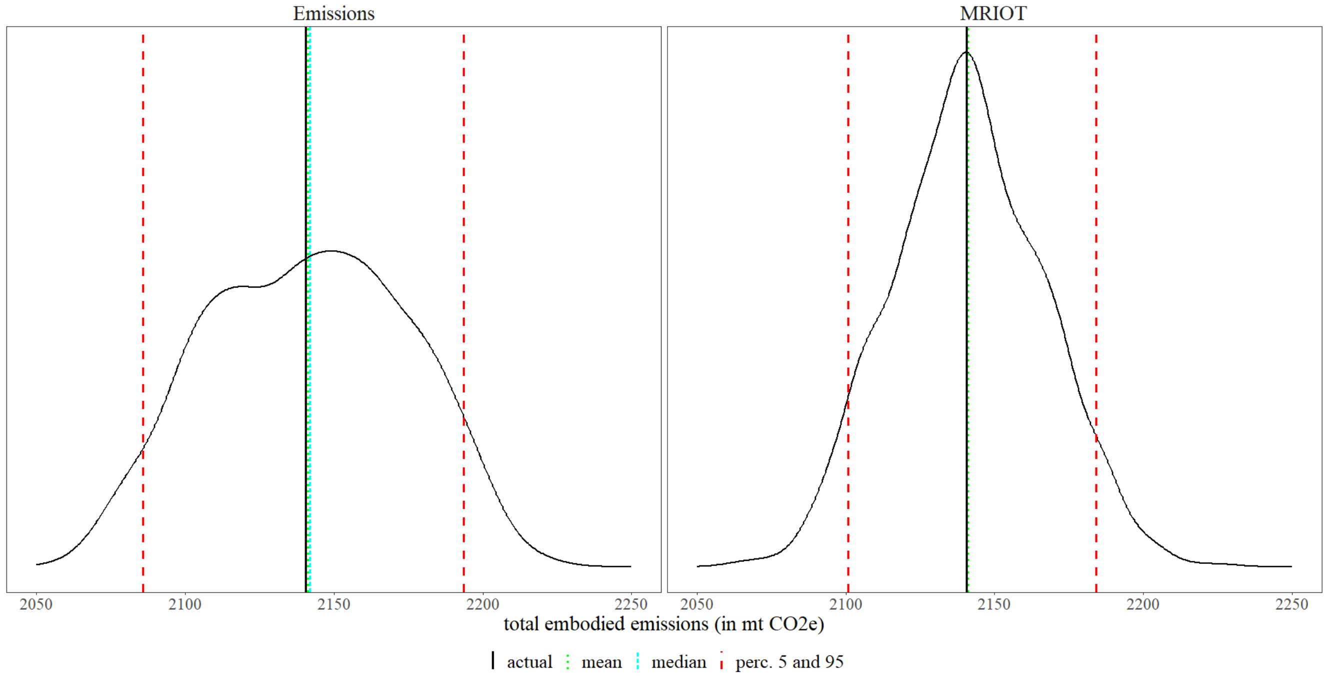
Supplementary Notes 2

To ensure the robustness of our results and quantify uncertainty, we employ a Monte Carlo parametric-based strategy. Specifically, we built on the intuition of Wilting (2012) (11), separating the sensitivity analysis between economic inputs and the emissions vector. In his study estimating uncertainties in the Dutch carbon footprint using the GTAP database, (11) applied uniformly distributed random perturbations to generate serveral modified technical coefficient matrices, from which the footprint computation can then be performed. Consistent with his approach, we also fixed the primary parameter (the uncertainty interval) at 10% and applied the same method to assess uncertainties with respect to reported emissions values and economic outputs.

A total of 2,000 simulations were performed using data from the year 2021.

Results

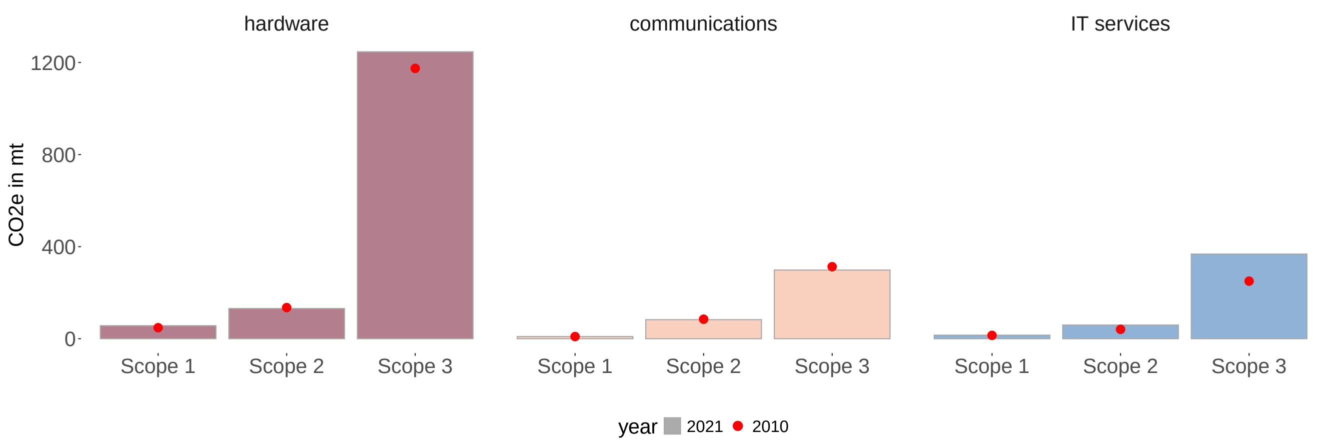
Results suggest that total digital emissions are not significantly sensitive to uncertainties in the economic data or the emissions vector. Marginal random perturbations do not substantially alter the magnitude of the results. In the configuration yielding the highest variance, which involves uniform draws of emissions with a 10% uncertainty level (Figure 1), 90% of the simulations fall between 2086 mt CO2e and 2194 mt CO2e. Perturbing the economic interaction system results in even lower uncertainty, with a standard deviation of 25 mt CO2e.



Supplementary Figure 1. Density plot showing the results of the uncertainty analysis replicating Wilting's intuitions (2012).

Supplementary Notes 3

Comparison of Scopes



Supplementary Figure 2. Comparison of between Scope 1, 2, and 3 emissions of total digital demand between 2010 (dots) and 2021 (bars) by industry. The displayed emissions are Scope 1, Scope 2 and Scope 3 of total digital demand. In this figure, we do not differentiate between embodied emissions that are associated with the final demand from digital industries and those that are mediated via other industries. Hence, embodied emissions overlap across industries and do not sum up to embodied emissions of total digital demand; see Table 3 for exact values and change rates in percent.

Figure 2 shows that scope 3 emissions of all digital industries are multiples of Scope 1 and Scope 2 emissions. This indicates that the majority of emissions occur upstream during the production of components integrated into digital technologies, and digital services (also see Table 3). Scope 1 emissions are at or below 5% of total embodied emissions of each industry. Scope 2 emissions account for approximately 10% of embodied emissions in the hardware industry, and 21% and 13% in communications and IT services, respectively. Higher Scope 2 emissions in communications and IT services can be explained by the energy-intensive nature of operating, e.g., telecommunication networks and data centers. Furthermore, IT services saw the largest increase in Scope 2 and Scope 3 emissions between 2010 and 2021. Both increased by nearly 50 %. This trend may be a predecessor of an even stronger increase, given the sharp rise in the adoption of AI services.

Additional data tables

Supplementary Table 2. Embodied emissions of total demand by category over time in kilotonnes (kt) CO2e (digital industries and digital emissions mediated via other industries)

year	IT services	communications	hardware	mediated via other industries
2010	179339.15	225286.88	854912.90	705748.90
2011	185484.81	237344.21	867427.78	739863.98
2012	204658.97	249019.35	857546.75	740135.81
2013	210424.68	236537.53	858424.76	767712.06
2014	203261.66	234082.53	828729.46	787842.18
2015	210953.41	221692.38	722835.13	789338.78
2016	210937.52	227784.09	665907.43	823320.09
2017	210836.64	233179.56	703691.92	837786.65
2018	220214.51	231825.45	724922.29	858630.52
2019	227758.13	219587.18	728145.97	879552.13
2020	225354.86	211811.47	720773.43	865169.88
2021	239622.62	219099.74	783173.84	898671.10

Supplementary Table 3. Comparison of scopes between 2010 and 2021 by industry in kilotonnes (kt) CO2e and change rates.

industry	scope	2010 (absolute)	2021 (absolute)	change between years in %	2010 (relative)	2021 (relative)
hardware	Scope 1	47876.32	56707.37	0.18	0.04	0.04
hardware	Scope 2	135259.56	131448.78	-0.03	0.10	0.09
hardware	Scope 3	1174348.69	1246585.36	0.06	0.87	0.87
communications	Scope 1	9397.10	9598.20	0.02	0.02	0.02
communications	Scope 2	84857.66	82814.85	-0.02	0.21	0.21
communications	Scope 3	312896.63	298489.86	-0.05	0.77	0.76
IT services	Scope 1	14552.76	15549.84	0.07	0.05	0.04
IT services	Scope 2	40656.36	59632.20	0.47	0.13	0.13
IT services	Scope 3	250154.36	367895.85	0.47	0.82	0.83

Notes: The columns '2010 (absolute)' and '2021 (absolute)' show absolute total embodied emissions by scope for each indsutry. The column 'change between years in %' shows the realtive change of absolute total embodied emissions between 2010 and 2021 by scope and industry. The columns '2010 (relative)' and '2021 (relative)' show total embodied emissions by scope realtive to the overall total embodied emissions by industry.

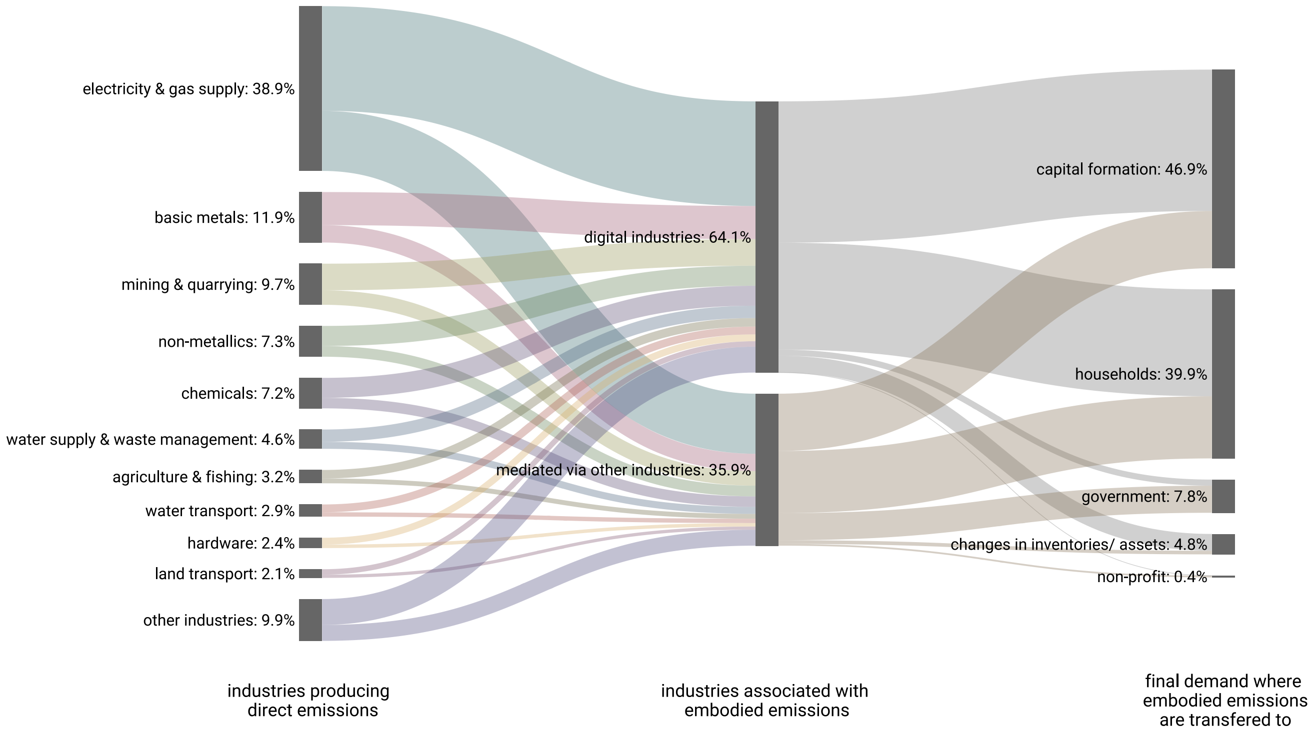
Supplementary Table 4. Embodied emissions mediated via other industries for 2010 and 2021 by industry in kilotonnes (kt) CO2e.

industry	2010	2021	change in %
hardware	502571.65	651567.67	30
communications	181864.51	171803.17	- 6
IT services	126024.33	203455.26	61

Note: Mediated embodied emissions of each industry do not sum up to total mediated embodied emissions as value chains overlap across industries. We replicated the same analysis on the three industries individually.

Additionally, looking at final demand by region (Table 5) provides insights into the amount of imported digital embodied emissions. Most embodied emissions stem from the final demand of domestic industries, but this share differs greatly between regions. Self-generated embodied emissions make up the largest share in China (96.51% in 2021), while the proportion is lower for Europe (Schengen + GB), 69.58%, and for the United States, 59.95%. This means that digital emissions from major Western countries' final demand include between a third and two fifths of imported emissions.

However, these patterns differ substantially across regions, as illustrated in Table 6. Looking more closely at the Chinese trends, approx. 18 % of the countries' digital embodied emissions come from investments in hardware and roughly 60% of the emissions related to digital industries embedded in Chinese final demand are associated with investment purposes. In comparison, the footprint structures in the US and Europe are more balanced, with investment and household consumption each accounting for around 40-50%.



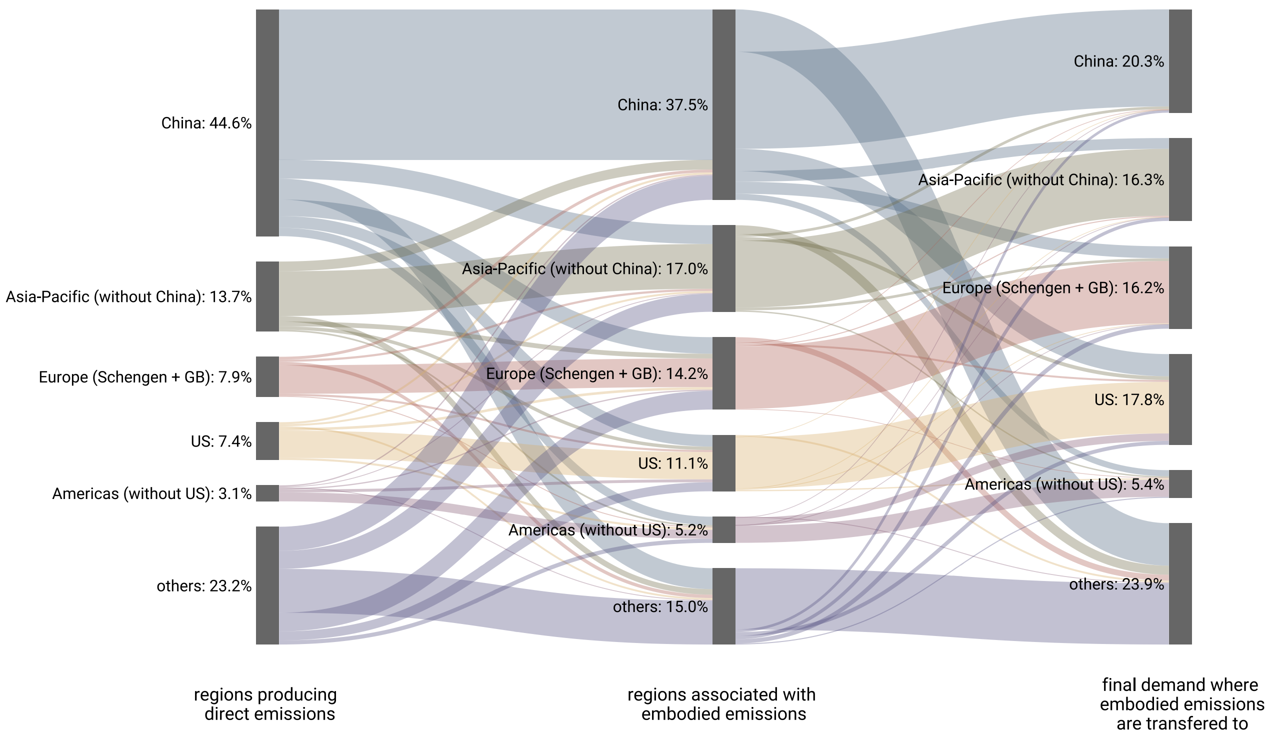
Supplementary Figure 3. Sankey diagram showing digital industries' emissions (in percent) with respect to different perspectives in 2010: left/direct emissions: in which industries emissions are being produced, middle/embodied emissions: embodied emissions within final products in the last stage of the value chain, right/final demand: embodied emissions by type of final demand.

Supplementary Table 5. Share (in %) of domestic emissions within final demand digital embodied emissions

Country	Share in 2010	Share in 2021
China	93.99	96.39
Rest of the world (Non-OECD)	77.10	79.53
European Union (28)	74.93	69.58
United States	56.84	59.95
Rest of the world (OECD)	63.46	57.26

Supplementary Table 6. Main drivers of digital emissions by industry and final demand category for different regions

	Combination between industry and final demand category			Overall distribution (%)	
Region	Industry	Demand category	Share (%)	Investment	Households
China	Hardware	Investment	18.24	58.33	28.01
EU 28	Hardware	Investment	17.34	42.05	41.00
United States	Hardware	Investment	19.33	41.09	51.38
ROW (OECD)	Hardware	Investment	20.65	42.72	40.74
ROW (Non-OECD)	Communications	Households cons.	24.57	38.68	51.48



Supplementary Figure 4. Sankey diagram showing digital industries' GHG emissions with respect to geographical locations in 2010: left / direct emissions: where emissions are being produced , middle / embodied emissions: embodied emissions within the final product/in the last stage of the value chain , right / final demand: embodied emissions by type of final demand.

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