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Pulling ourselves up by our bootstraps: the greenhouse gas value of products, enterprises and industries

Ulf von Kalckreuth

Deutsche Bundesbank, Wilhelm-Epstein-Straße 14, 60431 Frankfurt am Main,
Postfach 10 06 02, 60006 Frankfurt am Main

Tel +49 69 9566-0

Please address all orders in writing to: Deutsche Bundesbank,
Press and Public Relations Division, at the above address or via fax +49 69 9566-3077

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Non-technical summary

Research questions

This paper proposes a consistent system of indicators for the greenhouse gas (GHG) impact of industries, companies and products, from the top-level aggregate down to the level of single activities. The indicators condense information on the impact of GHGs for decision makers – in the policy arena as well as for investors, producers and consumers – in a way that is easy to interpret and process.

Contribution

The GHG value of a product is the total quantity of GHGs emitted in the course of production – directly and indirectly. Thus, GHG values are interdependent within the economic system. This paper makes three major contributions. First, input-output analysis makes it possible to study the information content of the indicator system. Second, the paper shows that, with strictly limited micro-level information exchange, the product-level indicator system can be generated in an almost entirely decentralised way. The GHG value of a certain activity or product is like a price tag, and in the same way as input prices are processed in cost calculation, the GHG value of activities and products can be passed along the stages of the value chain. As with financial costs, consumers or producers do not need to be aware of the stages of the value chain – they only need to know the GHG values of their immediate suppliers. This is shown formally and supported by an extensive micro-simulation based on sectoral GHG content in Germany. Third, with appropriate institutional underpinning, disclosure of GHG values may become largely self-sustaining. GHG values are easy to understand, manage and communicate.

Results

The theoretical argument and the simulation show that decentralised processing, i.e. information creation by market participants, is feasible. The information generated by GHG values is of high relevance for monetary policy in the transition to a low carbon economy, as price changes resulting from high carbon intensities can be separately identified. The paper develops a number of specific policy options for data strategies.

Nichttechnische Zusammenfassung

Fragestellung

Dieses Papier beschreibt ein konsistentes System für Indikatoren zu den Treibhausgasemissionen auf der Ebene von Wirtschaftszweigen, Unternehmen und Produkten, von den großen Aggregaten hinunter zur Ebene einzelner Aktivitäten. Die Indikatoren verdichten die Informationen zu GHG-Emissionen für Investoren, Produzenten und Konsumenten in einer Weise, die leicht zu interpretieren und zu verarbeiten ist.

Beitrag

Der *Treibhausgaswert* eines Produkts ist die Gesamtmenge an Treibhausgasen, die bei der Produktion emittiert werden, direkt oder indirekt. Damit sind die Treibhausgaswerte interdependent. Diese Untersuchung liefert drei wichtige Beiträge. Erstens wird mit Hilfe des Instrumentariums der Input-Output-Analyse der Informationsgehalt des Indikatorengeflechts beschrieben. Zweitens wird gezeigt, dass sich die Indikatoren auf Produktebene fast vollkommen dezentral und marktbasiert bilden lassen. Treibhausgaswerte sind wie ein Preisschild, und wie die Kostenrechnung Aufwendungen für Inputs verarbeitet, können auch Treibhausgaswerte in der Wertschöpfungskette weitergegeben werden. Wie bei finanziellen Kosten müssen Konsumenten und Produzenten mitnichten die gesamte Wertschöpfungskette kennen – es genügt, dass sie über die Treibhausgaswerte der vorhergehenden Stufe informiert sind. Dies wird formal gezeigt und durch eine Mikrosimulation auf der Grundlage deutscher Daten untermauert. Drittens wird aufgezeigt, dass in einem geeigneten institutionellen Rahmen die Offenlegung eine weitgehend selbstgestützte Dynamik entfaltet. Treibhausgaswerte sind leicht zu verstehen, zu verarbeiten und zu kommunizieren.

Ergebnisse

Die Analyse zeigt, dass dezentrale Informationsverarbeitung über Märkte realisierbar ist. Treibhausgaswerte sind von erheblicher Bedeutung für die Geldpolitik im Übergang zu einer kohlenstoffarmen Wirtschaft, da mit ihrer Hilfe die aus hohen Treibhausgasintensitäten bedingten Preisänderungen separat identifiziert werden können. Das Papier entwickelt eine Reihe spezifischer Optionen für amtliche Datenstrategien.

BUNDESBANK DISCUSSION PAPER NO 23/2022

Pulling ourselves up by our bootstraps: the greenhouse gas value of products, enterprises and industries[1]

Ulf von Kalckreuth
Deutsche Bundesbank

Abstract

This paper presents a system of greenhouse gas indicators for markets and policymakers. The system is lean and informative. It condenses the relevant product and enterprise-specific information into a single number: the greenhouse gas (GHG) value. Like prices, GHG values are easy to understand, manage and communicate. The envisaged scenario is one in which, at all levels of production, goods and services have two tags – the financial price to pay and the GHG value. GHG values are interdependent. The value for any product will depend on the carbon costs of all inputs. This paper shows that the massive information processing this simultaneity involves can be handed over to the market. Analytically, the system of product-level indicators is solved for the reduced form, the vector of true GHG values. This vector is shown to be the fixed point to which measurement will converge if producers compute GHG values using the information they have: data from their input providers if available, and estimates elsewhere. This amounts to a process of collective, decentralised learning. Technological changes will automatically be accounted for. A micro-simulation exercise is carried out based on sectoral information on production structure from Germany. The results indicate that convergence is fast. With appropriate institutional underpinning, the disclosure of GHG values by producers may become self-sustaining.

Keywords: greenhouse gas intensities, carbon accounting, green finance

JEL classification: Q56, Q51, C81

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[1] Contact address: Ulf von Kalckreuth, Deutsche Bundesbank, Postfach 100602, 60006 Frankfurt am Main, Germany. Phone: +49 (0)69 9566 6010. Email: ulf.von-kalckreuth@bundesbank.de. See von Kalckreuth (forthcoming) for an early version of this work under a different title. The author is Principal Economist-Statistician at the DG Statistics of the Deutsche Bundesbank. He is grateful for comments provided by an anonymous referee, Justin Dijk, Fabienne Fortanier, Robert Kirchner, Christoph Meinerding, Richhild Moessner, Karthik Ramanna, Martin Wagner, Caroline Willecke, Olga Wittchen, Monika Wozowczyk, Dilyara Salakhova, Tetti Tzamourani and Mark Weth, as well as from participants of the Workshop on Climate Research, Deutsche Bundesbank Research Centre in March 2021, the International Conference for Statistics on Sustainable Finance, Paris, on 14 and 15 September 2021, the ESCB Research Cluster Sustainable Finance Seminar in December 2021, a seminar of the CMFB Taskforce SuFIR in January 2022 and the 8th International Symposium on Environment & Energy Finance Issues (ISEFI) on 23 and 24 May 2022 in Paris. Lastly, the author wishes to thank the Lord for the ideas collected in this paper and the strength to develop them. This paper represents the author's personal opinions and does not necessarily reflect the views of the Deutsche Bundesbank.

1 Introduction and summary

This paper proposes a consistent system of indicators for the greenhouse gas (GHG) impact of industries, companies and products, from the top-level aggregate down to the level of single activities. The framework condenses information on the impact of GHGs for decision makers – in the policy arena as well as for investors, producers and consumers – in a way that is easy to interpret and process. It allows consumers, investors and policymakers to differentiate between goods, activities and firms based on their carbon impact.

The suggested indicator system and this investigation bring together three strands of scientific work: input-output (IO) methodology and its capability to keep track of indirect emissions in interlinked systems of production, the carbon accounting literature on how to evaluate carbon emissions in single companies, making "dual use" of financial, and the work on GHG Protocol emission classes in environmental reporting.

Generally speaking, policy and market participants need to attribute GHG emissions to economic activities: production of single goods, the output of firms, the product of sectors and countries. It is seldom sufficient to look at emissions as a by-product of an activity itself – in most cases of interest, there are inputs that generate their own emissions in production. It is only by considering both direct and indirect emissions that the institutional organisation of production in economic units becomes irrelevant and the total impact is revealed.

However, the link between direct and indirect emissions is not trivial. It becomes intensely relevant when measurement is looked at from the point of view of the economic system. What has been recorded as a direct emission in the production process of one good must add one-to-one to the indirect emissions of another if the first product is used as an input for the second.

The concept used in IO analysis for large-scale statistical aggregates is consistent in that respect. At the micro level, when measuring the direct and indirect emissions of enterprises or the carbon content of products, the measurement of indirect emissions in the GHG Protocol tradition is largely ad hoc and dissociated from the well-established measurement of direct emissions.

It emerges that, at the micro level, direct communication between the producer of an input and its user is needed to ensure consistency. The environmental liability of a product, or E-liability for short, has been suggested by Kaplan and Ramanna (2021a, 2021b) as a measure of the total quantity of GHG emitted in the course of production – directly and indirectly. Crucially, when buying an input, a producer will also "buy" the E-liability attached. The producer has to account for the E-liabilities acquired in a way that is similar to the reporting on the uses of financial funds, thus ensuring consistency between direct and indirect emissions, at least at a dyadic level.

The E-liability framework is reformulated using concepts of IO analysis, thereby adding important conditions for comparability between enterprises.[2] The result is a consistent system of indicators for the GHG impact of industries, companies and products, from the top-level aggregate down to the level of single activities. This measure has been christened the "GHG value". It combines and unifies three different but complementary perspectives: IO analysis, GHG Protocol guidelines and carbon accounting. This is the first contribution of this paper.

How can GHG values of outputs be calculated in a world where not all the GHG values of inputs are known? GHG values are interdependent – the value for any product will depend on the value of all inputs. Analytically, the setting makes it possible to express the value of a system of interlinked indicators as a reduced form. In reality, it would never be possible to compute the reduced form as the necessary information cannot be centralised. However, this is not needed. Showing this is the second main contribution of the paper: producers of final goods do not have to be aware of the stages of the value chain – they only need to know the GHG values of their immediate suppliers and their own technology. Starting from estimates and using the GHG values provided by their suppliers whenever available, the GHG values computed by producers will converge to the true values. Instead of centralised processing, the market will perform the task in a decentralised and iterative manner.[3] This is shown analytically, and the argument is supported by an extensive micro-simulation on the basis of sectoral data from Germany. The result on decentralised learning has a powerful implication: as technology and direct emission intensity change over time, the GHG measures provided by the market system will follow suit, staying informative, without the need for any central institution to take account and intervene.

These results have a simple intuition: GHG values are an analogue to economic value, with direct emissions playing the role of the value added of a production stage and indirect emissions corresponding to the value of intermediate inputs. Just as input prices are

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[2] The ideas in this paper have largely been developed independently by the author, around the notion of "carbon costs"; see von Kalckreuth (forthcoming). It was only in December 2021 that the author learned of the publications by Kaplan and Ramanna.

[3] This is analogous to the processing of information on economic scarcity in the price mechanism, as described by Hayek.

processed in cost calculation, the GHG values of activities and products can be passed along the stages of the value chain.

Third, looking at disclosure as a signalling game, the paper comes to the result that disclosure in a system of GHG values is largely self-enforcing, provided some basic institutional preconditions are in place and enough market participants actively use it. Disclosing GHG values will exert competitive pressure on other market participants to do the same.

GHG values are a synthesis of the frameworks provided by IO analysis and by E-liabilities. They are a linear, product-level measure in the tradition of IO, enhanced by an accounting framework and micro-level information exchange that make it work in a decentralised manner. Alternatively, it could be said that GHG values are a constrained version of E-liabilities, the restrictions being the linear structure and a space of inputs that is common to all production processes. These constraints make it possible to analyse the information content of the *interrelated system of indicators*, as opposed to isolated product-level indicators. This makes it possible to propose consistent sector-level measures for the imputation of missing input GHG values and to model the learning process. Both are important for making the concept operational.

The proposed framework allows consumers, investors and policymakers to differentiate between goods, activities and firms based on their carbon impact. GHG values can thus provide the granular-level information for climate mitigation issues that is so badly needed. Amongst other things, they may help central banks understand the implications of the transition to a low carbon economy for product prices. The concept may inform policy activity. New disclosure directives are beginning to take shape, but there is much that remains undefined. At the same time, central banks and international organisations are considering whether to assume an active role in sustainability issues in line with their mandates. The paper presents an outlook for both disclosure legislation and the role of central institutions.

Section 2 fleshes out the concept. It starts by giving a vision of how GHG values can work and serve society. Using IO analysis, the concept is set up to enable the tracking of production interlinkages. Next, GHG values are linked to carbon accounting and to GHG emission classes. Section 3 provides descriptive statistics at the company level. Sections 4 and 5 outline information requirements for setting up a comprehensive and informative system of GHG indicators. Over time, markets will "learn" the true values by interactively processing the available information, even if imperfect estimates are used where exact GHG values for inputs are missing. Section 6 shows that the disclosure of GHG values may be self-sustaining, while Section 7 develops policy options. Annex 1 gives detailed information on sectoral computations and the micro-simulation exercise. Annex 2 reviews IO models that may be used or expanded upon to approximate GHG values of inputs. Annex 3 gives an overview of the availability of microdata on emissions and describes some of the key legislative initiatives regarding mandatory disclosure of environmental information.

2 GHG value – the three perspectives

2.1 The vision

At the heart of environmental problems is a situation in which the effect that producing and using goods has on scarce resources is not properly reflected in the price system. In the case of GHGs, the scarce resource is the capacity of the environment to absorb carbon emissions – or, to be more precise, the maximum permissible quantity of carbon emissions in line with global warming targets.

For a massive reduction of GHG emissions, it is vital that consumers, investors and policymakers be able to properly evaluate the environmental consequences of production activities so that they can make the right choices as decision makers.

What is it one would ideally expect from an indicator system designed for climate mitigation and specifically for financial sustainability purposes? We need exact quantitative information on the relevant emissions at the level of both firms and products. All emissions, direct and indirect, need to be covered, the latter not as loose estimates, but based on realised material flows and micro-level production interdependencies. Granular information is notably scarce, especially at the Scope 3 level. But it is indeed granular information that is required to make meaningful distinctions that go beyond favouring products and firms in sectors with a low carbon intensity or selecting stocks that happen to be in high-tech sectors.

A metric that summarises the relevant information needed to make decisions on the production, use and consumption of goods and services is the *GHG value,* defined in this paper as the total amount of carbon equivalents emitted in the course of production of a good or service, either directly or indirectly through the use of intermediate input products.[4] As in IO analysis, the definition of indirect emissions is recursive, recurring to

[4] There are other terms for the amount of GHG emitted directly and indirectly in the course of production. "GHG content" is mostly used for IO measures, while the terms "GHG footprint" and "GHG intensity" are general and not tied to any measurement framework. The term "E-liability" is a concept proposed by Kaplan and Ramanna to characterise a process for collecting, processing and reporting information on GHG emissions in an accounting framework. In this paper, the term "GHG value" will be used for the system of

the GHG values of earlier production stages. The concept has two additional important complements: a process of information exchange between providers and users of intermediate inputs, as described by Kaplan and Ramanna (2021a, 2021b), and micro-level standards for the measuring of direct emissions, such as the one provided by the GHG Protocol. The concept and its components will be laid out in the following subsections.

There is a huge benefit in establishing and maintaining a system of reporting product-level GHG values. Consumers can use them to compare alternatives. If they prefer less carbon-intensive alternatives and are willing to pay the price, this creates competitive pressure. The pressure carries over to earlier stages of production: along the entire value chain, buyers of intermediate inputs will opt for less carbon-intensive alternatives. Administration and policymakers can be provided with a solid foundation for classifying firms – for taxes or subsidies, industrial policy or taxonomies for sustainable finance purposes. As an example: GHG value information is precisely what is needed to get EU plans for a carbon border adjustment mechanism off the ground.[5] At each stage of production, the metric captures and carries forward the environmental resources that have been used up to that point. In a peer group of goods that are close substitutes, GHG values allow for the identification of inefficient producers and production technologies. Regarding unrelated goods, consumers and policymakers can compare and weigh their respective usefulness against their consequences for the climate. GHG values are like a real rate of exchange between final products or inputs and their consequences for the environment. It is a quantity structure that makes it possible to trace the price effects of carbon reduction policies at all levels – an important input for monetary policy in the transition to a low carbon economy. It may also be used to derive targets for allocation purposes.

This is all that a measurement concept can give. The rest of this paper provides the methodology that will enable implementation. The key is the recursive nature of the metric and decentralised data generation from an exchange of information between buyers and sellers of inputs.

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indicators based on individual products that is discussed here, whereas for IO-based aggregate-level proxies, the term "GHG content" is preferred.

[5] As part of the European Green Deal, the European Commission intends to put a carbon price on targeted imports by 2026 to avoid "carbon leakage", i.e. the migration of industries to countries with more relaxed emissions policies. Technically, importers need to buy carbon certificates corresponding to the carbon price that would have been paid if the products had been produced in the European Union; see here official information with further links to the proposed legislation. Without a quantification of carbon content, the WTO may well consider the proposal an illegal tariff.

2.2 An IO view

The GHG value encompasses both direct and indirect GHG emissions as a consequence of the production of a good or service. Indirect emissions are the result of direct emissions in a chain – or rather a fabric – of other production processes. Those production interlinkages are key for the consistent treatment of indirect emissions. IO analysis is designed for this type of interlinkages, and in fact it has been used in tackling the issue of attributing resource consumption to final output at the sectoral level since the 1970s; see Section 4.1 and Annex 2. IO analysis makes the structure of an interlinked system of GHG values accessible. This makes it possible to suggest useful proxies for missing input valuations and to track analytically what happens when producers use them.

To fix ideas, consider the following. In production planning, every process is defined by a *bill of material* (BoM) that specifies all inputs, plus a *route sheet* that explains how to combine them. A complex production process may be decomposed into several stages. Consider the BoM of product *k*,

$$\mathbf{a}_k = \begin{pmatrix} a_{k1} & a_{k2} & \dots & a_{kK} \end{pmatrix}' \ ,$$

with a_{ki} being the quantity of good *i* that enters the production process. For reasons that will become apparent soon, there are entries for all input goods in the economy, most of them with a value of zero, of course. Let the amount of carbon emitted directly be given as d_k. Let scalar g_i be the GHG value of good *i*, the quantity of GHG that is emitted in the production of one unit. List the GHG values of all input goods in a vector as well:

$$\mathbf{g} = \begin{pmatrix} g_1 & g_2 & \dots & g_K \end{pmatrix}' \ .$$

The GHG value of product *k* is then given as the *sum of direct and indirect emissions.* Importantly, we do not add a definition for indirect emissions, but *simply define them recursively as the GHG values of inputs:*

$$g_k = d_k + \mathbf{g}'\mathbf{a}_k = d_k + \sum_i g_i a_{ki} \ . \qquad (1)$$

Indirect emissions are the direct emissions at earlier stages of the value chain. The equation is both perfectly general and encompassing. It relates to products and activities and – for a defined time span – to enterprises and sectors as well.

As it stands, this equation is a definition. It helps us understand the problems associated with gathering and processing information. For actual computation, all the g_i corresponding to the BoM of product *k* are required. If these are known, we can calculate the GHG value of product *k* in a straightforward way from direct emissions and the BoM.

This is like computing the energy content of food: it is enough that producers know the composition of their product and the energy content of the ingredients.

If the relevant elements of **g** are unknown, we can use equation (1) recursively and try to compute the GHG values involved, going up the value chain from more complex intermediate inputs down to primary and primitive inputs. It is helpful to note that equation (1) and the corresponding equations for all other goods constitute a simultaneous equation system. The structure is well known from linear production planning and IO analysis, pioneered by Wassily Leontief, and it was indeed the same author who first proposed using IO models for analysing pollution generation associated with inter-industry activity.[6] Conceptually, we can solve for the GHG values of all products simultaneously. Let

$$\mathbf{A} = \begin{pmatrix} \mathbf{a}_1 & \mathbf{a}_2 & \dots & \mathbf{a}_K \end{pmatrix}$$

be the matrix of the BoMs for all output goods, 1,…,*K*. With $\mathbf{d}$ being the column vector of the associated direct emissions, one may write:

$$\mathbf{g}' = \mathbf{d}' + \mathbf{g}'\mathbf{A}. \qquad (1)'$$

This structure is equivalent to the (open) Leontief model of production.[7] Reordering and postmultiplying the "Leontief inverse" $(\mathbf{I} - \mathbf{A})^{-1}$ yields:

$$\mathbf{e}' = \mathbf{d}'(\mathbf{I} - \mathbf{A})^{-1}. \qquad (2)$$

The GHG values of products (product *k* and all the others) result from their own direct emissions and the direct emissions of all the intermediate goods used for their production by intermediation of a matrix derived from the BoM that reflects the interlinkages in production. If the coefficients in the GHG equation refer to empirical production

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[6] Wassily Leontief was awarded the 1973 Nobel Prize for the development of IO analysis. Leontief (1966, 1986) covers much of his work. Leontief (1970) himself introduced pollution by augmenting the technology matrix to include a row of pollution generation coefficients; see Qayum (1991, 1994) for a consistent reformulation. The direct approach taken here, postulating a proportional relationship between output and pollution, was first advanced, on a sectoral basis, by Just (1974) and Folk and Hannon (1974). The formulations are equivalent. For IO analysis in general, see Miller and Blair (2009), and specifically Chapter 10 for environmental IO analysis. Suh (2010) is a collection of extensions and applications in the field of industrial ecology.

[7] Note that IO analysis is typically concerned with sectoral interlinkages, not with the product level. At the sectoral level, see Miller and Blair (2009), Chapter 10, for the extension of basic IO analysis to environmental issues. To be precise, the structure outlined in this paper corresponds to the "dual" price system that results from the Leontief structure, yielding a linear relationship between the values added of industries and the prices of goods; see Pasinetti (1977), Chapter 4.

technologies actually being used to produce goods, 1,…,K, it can be taken for granted that the inverse exists and all its elements are non-negative.[8]

As simple and beautiful as this relationship is, it is not possible to use it directly. Matrix $\mathbf{A}$ comprises the BoMs for all products in the economy, including those that have been imported, and if a certain input is produced using two different technologies, it should actually have two separate entries. Meanwhile, vector $\mathbf{d}$ collects the direct emissions that characterise all of these processes. Except for simple cases, this cannot be dealt with at the micro level. However, sector-level approximations of factor intensities using IO models are feasible, as will be explained later. And just as the price mechanism is able to process an enormous amount of information in a decentralised way, we can think of ways to make the coordinated exchange of information between producers do the rest of the work.

2.3 Micro-level information exchange: E-liabilities

Kaplan and Ramanna suggest recording direct emissions as an "environmental liability", or E-liability, and passing them on to the buyers of inputs, in the same way as a company's value added is passed on to the buyers of an input. According to their proposal, E-liabilities are *created* when a company emits greenhouse gas in the course of production. They are *acquired* when an intermediate input with an E-liability attached is bought. In this case, a GHG account of the seller is credited and the respective account of the buyer is debited. The E-liabilities corresponding to direct emissions and to purchased inputs will be assigned to products. The E-liability of the output will thus embody the direct emissions of all earlier stages. If the product is sold, either for final use or as an intermediate input to an external client, the company account is credited with the E-liability of that good. The E-liability characterises the product and is attached to it, and it leaves the firm with the output. On the other side, the GHG account of the buyer is debited. At the company level, any change in the E-liability over a given time interval will reflect the GHG content of inventory changes.

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[8] If some of the relationships are estimated, postulated or extrapolated from the past, as will be the case in real-world implementations, the existence of non-negative solutions $\mathbf{g}$ given non-negative elements in $\mathbf{A}$ and $\mathbf{d}$ cannot be taken for granted a priori. For a non-negative solution to exist, it is necessary and sufficient that all principal minors of $\mathbf{I}-\mathbf{A}$ are positive (Hawkins-Simon conditions). Equivalently, all characteristic roots of $\mathbf{A}$ are less than 1. See, for example, Takayama, (1985), Chapter 4, specifically the summary collection on p. 386. Intuitively, the amount of direct carbon emissions needed may not "explode" as we use equation (1) recursively. Iteratively, the Leontief inverse can be computed as a power series, $(\mathbf{I}-\mathbf{A})^{-1}=\mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots$. This expansion will converge if and only if the eigenvalues of $\mathbf{A}$ stay within the unit circle. Pasinetti (1976), Chapter 4, specifically pp. 66 ff. and the references to the appendix, and Schumann (1968), pp. 35 ff., give clear expositions.

Over the stages of the value chain, the E-liability of the output will thus embody the direct emissions of all earlier stages. E-liabilities are framed as a close, almost perfect analogue to costs. Both are *valued resource consumption.* The input vectors may figure both in cost accounting and in E-liability accounting, with only the valuation differing – for standard cost calculation it is financial prices, whereas in the context of carbon accounting it is the E-liabilities of inputs. This enables the use of standard accounting techniques, the outcome of centuries of experience with valuation problems. Actually, E-liabilities are fraught with a large number of such valuation issues: emissions from overhead activities such as the heating of production facilities and office buildings, transportation, the E-liabilities of capital goods, or combined production technologies. These require the *allocation* of company-level costs. The cost accounting solutions that exist simply need to be applied to the task of calculating E-liabilities. Kaplan and Ramanna leave it to the companies to decide just how they wish to allocate costs, provided that the accounting identities are respected and the allocation follows respected accounting principles. For an earlier literature review on carbon accounting, see Stechemesser and Guenther (2012) or, for a practical introduction, Eitelwein and Goretzki (2010). With a valuation vector for input goods at hand, it is possible to carry out information aggregation and processing using standard cost accounting software, both at the product and at the enterprise level.

The key contribution in Kaplan and Ramanna's suggestion is the implicit definition of indirect emissions, similar to the one in equation (1), and the establishment of unidirectional and extremely sparse communication between buyers and sellers of inputs: instead of revealing many details about technology and input sources, the seller passes on just one figure that embodies all the necessary information.

This raises a tough question, though. Whenever and wherever this system will start to operate, it will do so in a world where there are no E-liabilities for inputs from outside the company. How can those inputs be evaluated in E-liability accounting? The issue of missing valuations will persist, be it for imported goods or with regard to producers that will be exempt for a variety of reasons. Thus, in order to become operational, the concept needs to be adapted to circumstances in which input providers cannot or do not want to declare their E-liabilities.

By imposing additional structure, the analytical view developed here will allow us to do so. Note that by considering all GHG value equations jointly and solving them for the reduced form in equation (2), it is assumed that the definition of inputs is the same over processes. One may aggregate several inputs in the GHG equation for one process and consider them separately in another, but the valuations need to be consistent. This also means that the allocation rules should be the same or at least comparable. Without this restriction, E-liability measurement is consistent between buyers and sellers of inputs, but not necessarily comparable between firms producing similar or identical goods.

The GHG value framework exposed in Subsection 2.2 thus needs to be enriched with a precisely defined information structure. Alternatively, one could think of the GHG value framework as an E-liability protocol with restrictions on the classification of inputs and allocation rules. In any case, a protocol for the measurement of direct emissions covering all activities is also needed for comparability. A well-known and widely accepted rulebook for the measurement of direct emissions is provided by the GHG Protocol developed and supported by the World Resources Institute (WRI), see Annex 3.1, and the existing ISO norms visibly build on the GHG Protocol. The following subsection relates the GHG values to the GHG Protocol emission classes.

2.4 **GHG emission classes**

The GHG Protocol emission classes are widely used in environmental reporting (see Annex 3.1), so it is useful to rephrase the definition of GHG values in these terms. In the production of good k, let $sc1_k$ and $sc2_k$ be Scope 1 and Scope 2 emissions, and $sc3u_k$ be *upstream* Scope 3 emissions (cradle to gate). Then we have:

$$c_k = sc1_k + sc2_k + sc3u_k. \tag{3}$$

Conceptually, GHG values are equal to the sum of Scope 1, Scope 2, and upstream Scope 3 emissions. Scope 1 emissions $sc1_k$ are identical to the direct emissions d_k in equation (1). Scope 2 emissions, $sc2_k$, enter equation (1) as the indirect emissions $g_i a_{ik}$ resulting from a specific class of inputs, namely the purchased energy from utility providers. Upstream Scope 3 emissions, $sc3u_k$, are reflected in equation (1) as the indirect emissions $g_i a_{ik}$ related to all other inputs *i*.

The GHG value definition does not include downstream Scope 3 emissions. Downstream emissions critically depend on decisions to be taken by others, and their inclusion would destroy the recursive nature of the GHG value as they lead to double counting if later stages of production use E-liabilities to evaluate their inputs.[9] Equation (3) ensures that

[9] One could choose to define GHG value slightly differently in terms of GHG *input* (as opposed to *emissions*) in order to take account of the physical carbon content of the product that will lead to emissions at a later stage. If d_k in equation (1) is the direct carbon input into production at the given stage rather than direct emissions, then g_k and all the $g_i, i = 1,...K$ are to be interpreted as physical carbon content, emissions included. The difference between this concept and the one given in equation (1) would largely be waste disposal emissions as a part of downstream Scope 3 emissions.

we can make use of GHG Protocol standards for data gathering and processing, specifically the binding norms relating to Scope 1 and 2 emissions.

The definitions are not equivalent, though. The difference lies in the indirect emissions component. In equation (1) for GHG values, they are accounted for recursively – the measurement content of indirect emissions thus *derives directly from the definition of direct emissions*, as the indirect emissions are just the direct emissions of earlier stages. The GHG Protocol standards regarding Scope 3 emissions allow for a number of options that partly reflect content, partly measurement. The carbon emissions of commuting workers, for example, are difficult to monitor and only loosely related to the company and its product.[10] In the GHG value equation, this sort of option can be accommodated by restricting the inputs to be considered. Other GHG Protocol options reflect the differing availability of information. In practice, the pronounced optionality renders the measurement of Scope 3 emissions rather useless, as the resulting values lack comparability and are prone to opportunistic measurement choices by reporting companies. Indeed, data providers of GHG information routinely ignore Scope 3 disclosures of companies entirely and replace them with their own model-based estimations. The GHG Protocol measurement concept is not recursive. It obliges the producer to itself gather all the quantity information regarding emissions at earlier production stages. While this may be feasible for short and simple supply chains, it is impossible in the face of the massive interlinkages that characterise many modern industrial production processes. Typically, producers will not even know all the inputs of earlier stages.

With GHG values, the assumption regarding the information set of the producer is quite different: the producer is *not* required to understand the technology of prior stages. We do not even need a measurement concept for indirect emissions beyond what has been specified for the measurement of direct emissions and the BoMs defining the inputs. Instead, the concept requires GHG values for input goods, i.e. direct or indirect communication between suppliers and users of intermediate inputs.

Kaplan and Ramanna (2021b) massively criticise the GHG Scope 3 measurement as the "fatal flaw" in ESG reporting, as the "difficulty of tracking emissions from multiple suppliers and customers across multi-tier value chains makes it virtually impossible for a company to reliably estimate its Scope 3 numbers" (p.5). Though this is true, it needs to

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[10] For direct emissions and the use of energy, see the standards for disclosure of GHG Scope 1 and 2 emissions: WRI and WBCSD (2004). For Scope 3 (indirect) emissions, see the two closely related standards for enterprise-level and product-level disclosure: WRI and WBCSD (2011a and 2011b). Further, see the Technical Guidance for Calculating Scope 3 Emissions in WRI and WBCSD (2014).

be recognised that E-liabilities or GHG values have information requirements of their own, and that, depending on the situation, these may be hard to fulfil. Where there is no GHG value available for inputs, direct assessment may be needed. And concerning the inputs being considered, there are choices to be made in a GHG liability system, too. To maintain comparability, these choices need to be reflected in binding rules, at least for broad classes of activities. Full implementation of a GHG value indicator system will bear elements of both approaches.

Result 1: *The GHG value of an activity or product is a simple recursive metric for climate effects, enhanced by direct communication flows between buyers and sellers of inputs. The concept borrows the analytical framework from IO, the communication process and the accounting framework from Kaplan and Ramanna, and the measurement of direct emissions from the GHG Protocol standards. In a production system, this yields a set of indicators that allow consumers, producers and policymakers to make informed decisions. Corresponding metrics can be calculated for enterprises and sectors. They are consistent with carbon content or intensities from IO models and with emission classes according to GHG Protocol standards. Given GHG values for inputs, the computation for a product or an enterprise can rely on established cost accounting procedures.*

3 GHG values of company output: some descriptives

Equation (3) permits us to look at the GHG value of output at the (aggregate) company level.[11] Since the GHG Protocol first published emission reporting standards in 2001, an increasing number of companies have been voluntarily reporting on Scope 1, Scope 2 and even Scope 3 emissions. This information is collected by centralised data platforms, with CDP being the most prominent. Commercial providers augment them with imputations on missing data and estimations to give investors a broad information base; for details, see Annex 3 to this paper.

Based on equation (3), estimates of GHG values for company-level output can be computed if information on the components of emissions according to scope is available. This is the case for the emissions data of Trucost.[12] In this section, they will be used to show some stylised facts and provide initial insight into magnitudes.

[11] In the Kaplan and Ramanna framework, the E-liability of a company is strictly distinguished from the E-liability of its output. When a product is sold, the E-liability assigned to it will be subtracted from the stock of the company; see Subsections 2.2 and 2.3. We may, however, compute the E-liability of the company's output as a flow.

[12] Trucost is an affiliate of S&P Global.

For 2019, Trucost reports GHG emissions data on 19,405 companies, most of them listed. Among them are 4,576 companies from China, including Hong Kong, 3,134 from the United States, 2,397 from Japan and 343 from Germany. Only a fraction of these emissions data are collected in their entirety from company disclosures: 9.2% of the Scope 1 emissions data worldwide and 19.8% from Germany are collected as exact figures. Fortunately, reporting incidence is much higher for large companies. Weighted by revenues, 69.9% of Scope 1 emissions data worldwide and 81.1% in Germany are collected as exact figures from company reports. The rest are either derived from partial information or estimated using the Trucost environmentally extended (EEIO) model. Trucost also reports upstream and downstream Scope 3 emission intensities. For upstream Scope 3 emissions, the agency does not make use of reported information: all data are estimated using a proprietary EEIO model.[13]

Table 1 lists descriptive statistics on company-level emission intensities (normalised by revenues) according to scope, namely the sum of Scope 1 and 2 emissions, the Scope 3 emissions, and the resulting E-liabilities of output. The table provides descriptive information on intensity ratios and logs. The Trucost database contains both holdings and operating companies, thus there may be some double counting. The data have not been cleaned to remove outliers.

Table 1: Company-level GHG emission intensities and GHG values

Trucost environmental data, 2019, worldwide

	Mean	**Median**	**Std Dev**	**# Obs**
Intensity levels				
Scope 1	288.35	17.20	1988.56	19,405
Scope 2	50.20	15.76	334.85	19,405
Scope 3 upstream	160.29	97.70	197.07	19,405
GHG value	498.84	169.84	2073.89	19,405
Log intensities				
Scope 1	2.834	2.845	2.205	19,405
Scope 2	2.748	2.757	1.497	19,405
Scope 3 upstream	4.577	4.582	0.990	19,405
GHG value	5.150	5.135	1.266	19,405

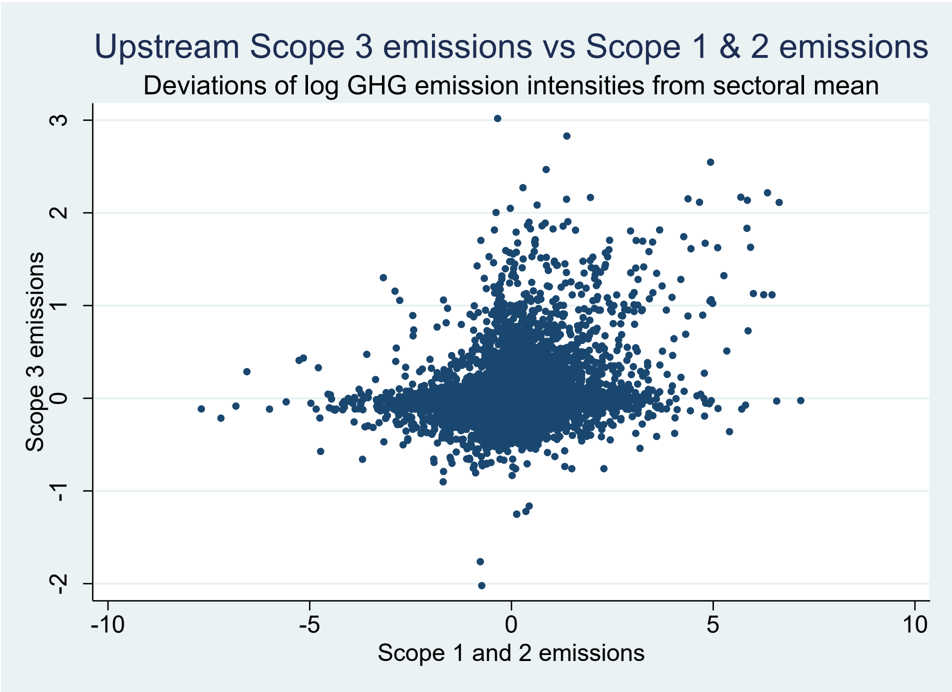
[1] Emission intensities are given as metric tons of CO_2 equivalents, normalised by company revenue in USD million. Scope 1 emissions are direct emissions, Scope 2 emissions are purchased electricity, heat and steam. Scope 3 upstream emissions are indirect emissions that result from intermediate inputs other than purchased electricity, heat and steam. GHG value is measured according to equation (3) as the sum of Scope 1, Scope 2 and estimated upstream Scope 3 emissions. All data are reported unweighted.

Sources: Trucost environmental data, author's calculations.

[13] Downstream emissions data make partial use of reported information.

Scope 1 and 2 intensities are highly skewed. The standard deviation is dominated by extreme values; it is much higher than the mean. The upstream emissions, being fully estimated, do not contribute much to the variability of the E-liability measure, although in terms of levels they have a share of around one-third. The logs are far better behaved. Means and medians are about equal. With log intensities, average upstream Scope 3 emissions are larger than Scope 1 and 2 emissions. For GHG values, the GHG content of inputs is of central importance.

Graph 1: GHG values of company output – main components



Source: Trucost environmental data, author's calculations.

Much of the information on intensities is associated with the sector of the producer. This is especially the case for estimated Scope 3 emissions. It would be interesting to see the extent to which the estimated Scope 3 emissions can actually contribute individual variation beyond the level information from the sector. To this end, the deviations of log intensities from their sectoral means are computed.[14] Graph 1 plots the mean deviations of log Scope 1 and 2 intensities against the mean deviations of log Scope 3 intensities. It is evident that the dispersion of Scope 3 mean deviations is lower than those computed

[14] The standard deviation of this measure takes a value of .9273174 for direct (Scope 1) emissions in 2019. Regarding Scope 2 and Scope 3 emissions, the standard deviations are .835826 and .2129105, respectively.

from Scope 1 and 2 emission intensities, but Trucost Scope 3 emissions data still contain a considerable amount of independent information.

4 Towards informative GHG valuations

As equation (1) shows, a producer's problem of calculating GHG values is recursive. Imagine for a moment that the producer knows the GHG values of inputs. Then they only need to allocate direct emissions and set up a detailed list of inputs for their products based on the knowledge of their own production technology. This may be called a *Hayekian situation:* just like the price system, the resulting system of GHG values embodies all the technology constraints and interdependencies of the entire system, without any individual producer having to know more than their own technology and the E-liability vector common to all agents.

In general, however, producers will be ignorant of the GHG values of their inputs. On the way towards the Hayekian situation, there is much to be gained from a valuation vector that is only approximately accurate. It gets the proportions right and makes environmental accounting independent of the level of vertical integration. Market participants and the administration obtain product and enterprise-level information on Scope 1, 2 and upstream Scope 3 emissions into which the producers' knowledge of production technology and the composition of inputs is fully incorporated. At this time, the information available at the enterprise level is on Scope 1 and 2 emissions at best; information on Scope 3 emissions is a rare exception, while product-level information is virtually absent.

Thus, to start with, we may assume that no granular, product-level valuation vector for inputs is available. *What happens if every producer is willing to make their best estimate and provide it for others to use?* It is shown in Sections 4.3 and 5 that decentralised information processing will reveal the true GHG values in equilibrium. In practical terms, producers can use their BoM with the GHG values provided by their suppliers, if available. If not, GHG values of reference products or sectoral approximations from IO models can be used instead. *The resulting indicators will converge to the true GHG values.* To get this process started, we need approximations for the GHG value of inputs.

4.1 Top down: generating proxies from sectoral IO models

Conceptually, IO models are the appropriate approach to deal with the recursive nature of the GHG value definition.

The total emission intensity of a sector, as calculated from an IO model, can be used as a sector-level proxy for input GHG values on the right-hand side of equation (1). In principle, GHG intensities can be calculated with any IO model that depicts the relevant industry interlinkages, provided that appropriate sector-level information on direct emissions is available. Smeets, Schellekens, Bowens and Wilting (2021) or Wilting and Oorschot (2017) give recent examples for the Dutch economy: they compute environmental footprints for a large variety of environmental externalities on the basis of interregional IO models. IO models with a focus on environmental issues are called environmentally extended IO models, or EEIO models.

Given the strong interdependence of national economies, the IO base should be international and not treat the "rest of the world" as a black box. In order to capture heterogeneity, the model ought to distinguish between a variety of sectors, possibly considering certain types of firms separately.[15] Ideally, the IO model would come near to providing GHG value proxies at a product level. Therefore, fine distinctions are needed, especially in sectors with strong industry interlinkages, e.g. manufacturing. Data quality is of paramount importance, however, and there is no use in trying to make distinctions that cannot be supported with existing data.

Annex 2 gives a short overview of some of the existing IO databases potentially suitable for generating proxy information on input emission intensities.

Result 2: *Carbon content according to EEIO models may serve as an industry-level proxy for the E-liabilities of inputs according to equation (2). In the case of missing product or firm-specific information on inputs, we can use the GHG intensity of the respective industry to generate product-specific GHG value proxies in equation (1).*

This allows producers or analysts to characterise the GHG values of inputs on an industry-by-industry basis. It yields initial values for an iterative approach. Near the front end of the supply chain, producers can compute rather accurate GHG values using sector proxies for their inputs. Further down, producers will still obtain consistent and mean-preserving estimates to be incorporated into their detailed micro-level knowledge of production technology.

[15] In analysing global value chains, Fortanier et al. (2019) suggest distinguishing between multinational enterprises and domestically controlled firms. The production technology of MNEs as well as their import content and export orientation are sources of intra-industry firm heterogeneity. In the same vein, in some developing countries one may want to distinguish between informal and formal activities within the sector, as the former may be less responsive to government environmental policy.

4.2 Other approximations for input GHG values

Using sector-level intensities from EEIO models is indeed one of the ways proposed by the GHG Protocol guides for calculating Scope 3 emissions. There are other ways of obtaining estimates. The GHG Protocol guides generally recommend an in-depth and detailed analysis of the entire product value chain. Producers are requested to make an effort to gather intelligence on Scope 1 and 2 emissions at earlier stages. While this is feasible in cases where producers oversee the entire value chain, or within the confines of the same group, it is tedious and impractical in the more general case of dispersed production activity. Input suppliers will not be forthcoming with providing detailed technological information to their B2B customers. The beauty of GHG values is that they encapsulate all required information on carbon use without disclosing anything technology-related beyond this, not even the amount of direct emissions.

Apart from the investigation of the supply chain, the GHG Protocol recommends the use of proxies and of firm-level information on the emissions of the provider. Known GHG values can be used for close technological substitutes. Using standardised intensities is especially practical for staple goods, where there is little technological variability. Low-intensity goods and services such as banking and insurance can be grouped and accounted for by using an overhead factor common for the industry of the producer. If the product-level GHG value is not available but the input provider publishes enterprise-level GHG Scope 1 and 2, or even Scope 3, emissions, the resulting intensities can be used as a basis for an estimate, similar to EEIO sector-level intensities. Section 3 above has taken a first look at such intensities. If they contain direct information on Scope 1 and 2 emissions, enterprise-level intensities are preferred to their sector-level counterparts, even if the Scope 3 emissions figure is based on estimates.

4.3 Bottom up: pulling oneself up by one's bootstraps

With initial values for the GHG values of inputs, e.g. from sectoral or firm-level intensities, the GHG value of a product can be calculated according to equation (1). This will not immediately lead to a consistent set of measures: typically, the GHG value g_k calculated according to equation (1) will not be equal to the approximations used for the input of the same good in calculating the E-liabilities of other products.

Importantly, however, each producer will be able to pass a measure of GHG values on to the buyers of intermediate products. Assume that, along with the price of the product, producers communicate GHG values. This allows for a *second stage*. If the buyers of intermediate products use the approximations of their suppliers instead of the industry averages, the estimation error will diminish greatly, as the direct emissions of intermediate inputs are correctly accounted for. In equilibrium, the error will disappear completely, provided there are no products without proper GHG content estimates, such as imports. It is easy to see why: industry averages or other approximations are needed only when there is no individual-level GHG content available. If there is one such measure for every good, and if these measures are consistently used to evaluate inputs according to equation (1), and if this evaluation reproduces itself for all goods, the industry averages will never enter the picture, not even indirectly.

The following will show convergence formally and derive an expression for its speed. From equation (2) and footnote 7, we have:

$$\mathbf{g}' = \mathbf{d}'\left(\mathbf{I}-\mathbf{A}\right)^{-1} = \mathbf{d}'\left(\mathbf{I}+\mathbf{A}+\mathbf{A}^{2}+\mathbf{A}^{3}+\ldots\right). \tag{4}$$

We may study the evolution of GHG value computations that start with a "wrong" set of GHG values, but with accurate direct emissions and input coefficients from the BoM. Let $\tilde{\mathbf{g}}$ be the vector of GHG values used as an approximation in the first round by all firms, such as using sectoral averages from EEIO models. In the first round, the estimate according to equation (1) for product *k* will be:

$$g_k\big|_1 = d_k + \tilde{\mathbf{g}}'\mathbf{a}_k .$$

For the entire set of products, we accordingly have:

$$\mathbf{g}'\big|_1 = \mathbf{d}' + \tilde{\mathbf{g}}'\mathbf{A} .$$

This set of product-specific GHG content measures is supposed to be passed on to the buyers of inputs, thus feeding into the second round computation:

$$\mathbf{g}'\big|_2 = \mathbf{d}' + \mathbf{g}'\big|_1\mathbf{A} = \mathbf{d}' + \left(\mathbf{d}' + \tilde{\mathbf{g}}'\mathbf{A}\right)\mathbf{A} = \mathbf{d}'\left(\mathbf{I}+\mathbf{A}\right) + \tilde{\mathbf{g}}'\mathbf{A}^{2} .$$

In round *n* we arrive at:

$$\mathbf{g}'\big|_n = \mathbf{d}'\left(\mathbf{I}+\mathbf{A}+\mathbf{A}^{2}+\ldots+\mathbf{A}^{n}\right) + \tilde{\mathbf{g}}'\mathbf{A}^{n+1} . \tag{5}$$

The first expression on the right-hand side is simply the step *n* matrix expansion for the true GHG value vector in equation (4). It will converge to $\mathbf{g}'$, no matter how good or bad the initial estimate is. The second component can be interpreted as an estimate of the missing part of the expansion, based on the initial estimate. If this initial estimate happens to be correct, then $\mathbf{g}'\big|_n$ is identically equal to the true GHG value, as one may see by substituting $\tilde{\mathbf{g}}'$ by the matrix expansion of $\mathbf{g}'$ according to (4). The speed of convergence thus depends on the size of the largest eigenvalue of $\mathbf{A}$, and in each iteration, the GHG value estimates will be better if the initial estimate vector is near the true value. We arrive at:

Result 3*: If all producers give a fair estimate of equation (1) using the information they have, i.e. direct emissions, BoMs, and GHG values of input or estimates thereof, and if this information is passed on to the market, in equilibrium the resulting system of GHG values will correctly reflect the interlinkages as given by equation (2).*

This is key for feasibility: producers *do not need to know the GHG values for products in the entire economy, only those of their own suppliers (or estimates thereof)*; just as for financial cost accounting we do not need to know the entire price system, but only what our suppliers charge. This is indeed the information set of Hayek's "man on the spot". The system will work if GHG value information from prior stages of production reach him. If not all E-liabilities are available, producers can use proxies, either from reference products or from sectoral models. Over time, the system will converge.

This result answers yet another important question – how are changes in the production processes to be dealt with? In IO terminology, the matrix **A** is evolving continuously, reflecting changing relative prices, technological progress and environmental legislation. For central data processing, including at the sectoral level, this is a paramount problem, as the database for calculation is invariably outdated. Result 3 tells us that the system of E-liabilities will adapt to any change of input intensities, without anybody having to take account of them, except the producers themselves!

We can look at this as *social learning* – the participants of the production systems are like interconnected, information processing neurons. The following section will illustrate this learning process in a simulation exercise that mimics the structure of interlinkages in the German economy.

5 A micro-simulation experiment on decentralised learning

5.1 Simulation set-up

The exercise involves carrying out the experiment described analytically in the last subsection: imagine that producers try to compute GHG values for their products into measurement equation (1) based on their BoM and incomplete information on the GHG values of inputs. If available, they will use GHG value indicators provided by their suppliers. If not, they will substitute estimates derived from aggregate statistics into the equation. They will pass the resulting indicators on to their clients. Thus, in the first round, all information on GHG values comes from sectoral averages. In subsequent stages, input indicators will be product-based. The purpose of the simulation is to see how the system evolves.

On the basis of statistical information on Germany for 2018, the author has simulated a system of products, each belonging to one of 71 product groups. For these product groups, the information on sectoral production interlinkages is available from Destatis IO tables.[16] Information on direct emissions in metric tons of CO_2 equivalents is available for a slightly less detailed set of 54 product groups[17] and can be made congruent to the IO table by allocating emissions to product groups on the basis of output weights.

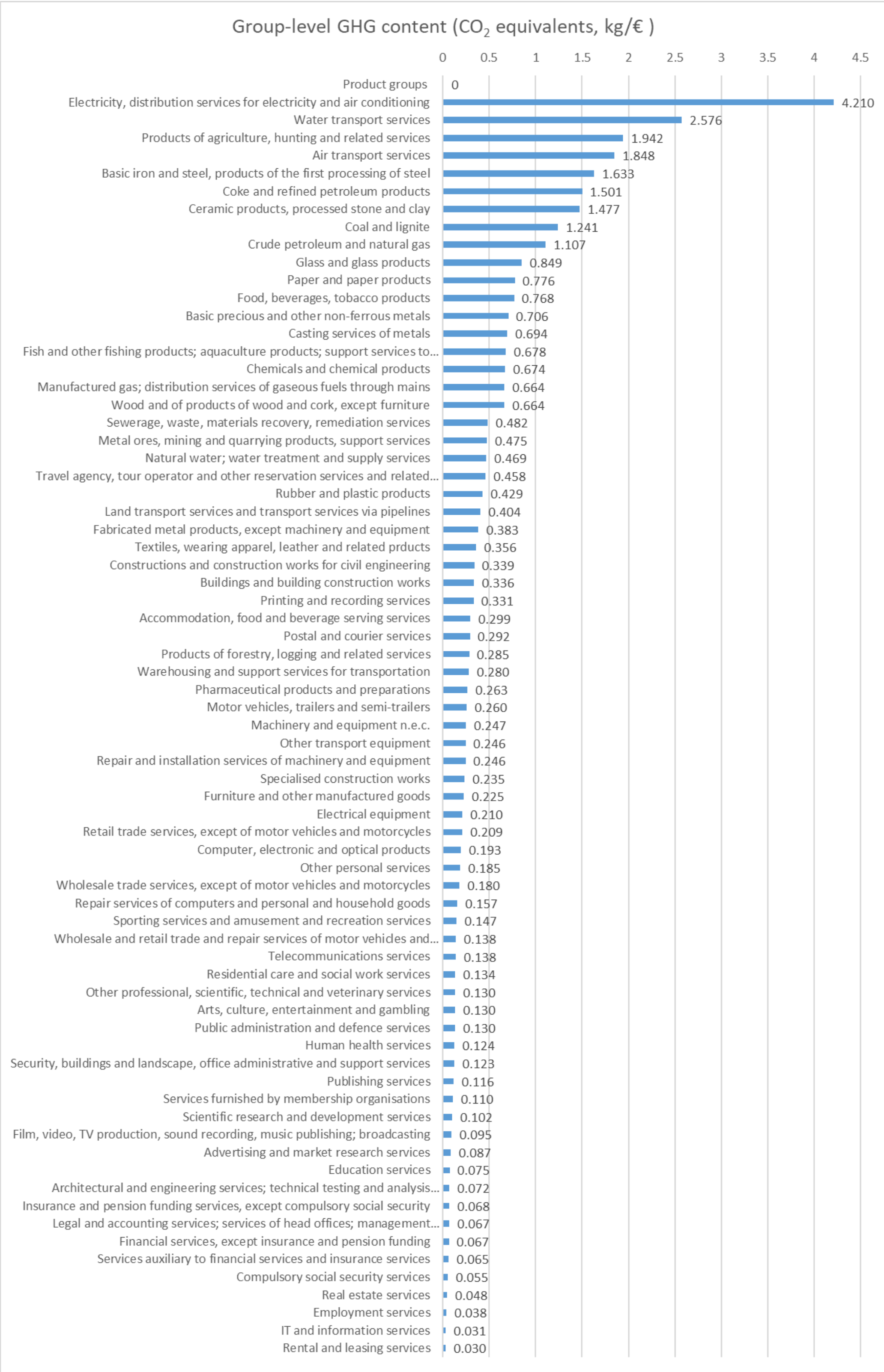
The simulation starts by calculating average sectoral GHG content, both in order to obtain parameters for the micro-simulation and as inputs for the initial estimation of producers. For computations, the author uses the IO matrix for total production plus imports and the emission intensity calculated as national emissions over national production by product group. This assumes that production abroad is carried out with the same technology as national production. The shortcut is not satisfactory, but certainly more appropriate than considering only national production interlinkages in calculating GHG values. The results for sectoral GHG content are shown in Graph 2. See Section 5.2 for a discussion.

For each product group, a number of simulated granular products are created, broadly proportional to total use (including imports). Each of the 7,699 products accounts for around €1 billion of total use. A matrix of production interdependencies for these simulated products is set up, where the input coefficients are inherited from the IO input coefficient matrix, multiplied by a lognormal individual-level disturbance term. For ease of computation, each of the products uses at most one input per product group, chosen at random from the products in that group. The size of the disturbance term that describes the heterogeneity of input coefficients is calibrated to reproducing the standard deviation of log mean deviation of Scope 2 emissions in the Trucost dataset; see Section 3. The variability of purchased energy is interpreted as an indicator for the variability of other inputs.

[16] See Destatis (2021a).

[17] See Destatis (2021b). The product groups in direct emission statistics and IO tables differ mainly in the level of granularity for service industries. The manufacturing output groupings are essentially identical.

Graph 2: GHG content for product groups, Germany 2018



Author's estimates and computation, based on Destatis (2021a) and Destatis (2021b); see Annex Table 1 and Section 5.1 for explanations.

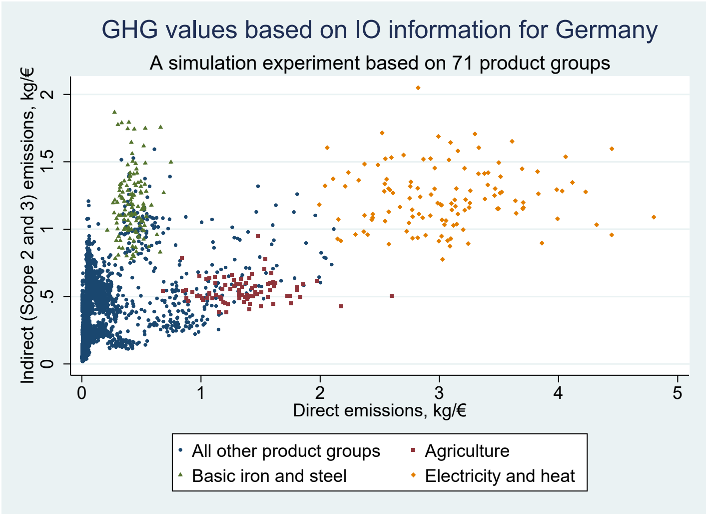
The input coefficients matrix for the moderate number of products in the simulation has a size of $7{,}699^2$ cells, almost 60 million. This is enough to see that a centralised approach is not feasible for any realistic set of products.[18] Direct emissions are modelled after direct emissions statistics for product groups by calculating emission intensity at the sectoral level and then submitting those intensities to a multiplicative lognormal disturbance that reproduces the standard deviation of log mean deviations of direct emissions in the Trucost dataset. Thus, the model is essentially an inflated and stochastic version of sectoral IO tables and direct emissions data for Germany, calibrated to reproduce the micro-level within-sector heterogeneity of direct emissions and Scope 2 emissions as found in the Trucost data.

Each individual column in the large micro-level input coefficients matrix is the BoM for one product, as defined for equation (1). With the matrix and the direct emissions at hand, GHG values are calculated directly, on the basis of equation (2), to serve as a point of reference. The simulation then traces the evolution of GHG value measures in a situation where each producer only knows the input coefficients of their own product and the best effort GHG value estimates of others, as explained in Section 4 above. This can be carried out on a much smaller and decentralised information base, and the micro-simulation allows a study of whether and how fast decentralised learning converges to the true value.

Graph 3 displays the resulting distribution of direct emission versus indirect emission intensities. Three sectors have been singled out visually. Electricity and heat are the source of Scope 3 emissions, and they are characterised by very high direct and indirect emissions per unit of output. The GHG intensity of agriculture is also high, specifically because of CH_4 (methane) due to livestock farming and NO_2 (nitrous oxide) due to fertilisers. Lastly, basic iron and steel are characterised by high indirect emissions, mostly due to heavy use of products from the same sector.

[18] Run time is about two hours in the author's notebook for setting up the input coefficient matrix and computing the Leontief matrix and the steps of the matrix power expansion in Stata 16.0. Computing 60 million lognormal shocks from uniform random numbers takes up much of that time.

Graph 3: GHG values -- simulating 7,699 products based on German data



Author's estimates and computation, based on Destatis (2021a) and Destatis (2021b).

5.2 Step 1: Sectoral GHG content and product-level GHG values

The results are presented in Annex Table 1. The first two columns show total use including imports and total use from national production only, as recorded in the national accounts. The third column shows direct emissions in metric tons of CO_2 equivalents, in some cases estimated by splitting up larger aggregates. Column 4 and Graph 2 above give the *GHG content by product group*, calculated from direct emissions and production interlinkages by computing the sectoral Leontief matrix as in equation (2).[19] As expected, electricity stands out, together with air and water transport. It is quite noteworthy that German agriculture has a higher GHG content per euro of output than all other industries except electricity and water transport. Total GHG content is equal to the sum of direct emissions in Germany plus the GHG content of imports. This accounting identity holds true in the sector-level computations.

The product group-level GHG contents have been calculated here for the purposes of a simulation exercise, and they are not meant to provide statistical information. Still, as a consistency check they can be compared against the results for Germany in Destatis (2018). This publication gives a detailed evaluation of the carbon content of final use in 2008 to 2015. Dividing the carbon content of final use for 2015 by the euro value of final

[19] For clarity, the author would like to point out that economic allocation decisions should not be made directly based on sector-level data unless it has been shown that there is little micro-level variation.

use of the same year,[20] one obtains a set of coefficients that can be compared with the 2018 sector-level carbon content calculated here. In spite of the differences in the reference year and some important methodological aspects,[21] the figures compare well for the GHG content of overall production, electricity and heat and the large industrial and service sectors.

In Annex Table 1, the columns to the right of column 4 introduce the product-level micro-simulation. Column 5 gives the number of products per product group. Columns 6 and 7 are the sector averages and standard deviations of product-level GHG values calculated directly by inverting the product-level Leontief matrix. As the underlying shocks to the input coefficients and the direct emission intensities are multiplicative, the standard deviation of GHG values is roughly proportional to size. The next three columns yield the components of GHG values by showing direct emissions, Scope 2 emissions and total indirect (Scope 2 and upstream Scope 3) emissions separately.

5.3 Step 2: Decentralised learning – looking at producers' information processing

The last three columns on Annex Table 1 describe a decentralised and collective learning process on the part of producers. Market participants pull themselves up by their bootstraps. Starting from the sectoral averages given in Column 3, GHG estimates are computed by the matrix power expansion algorithm in equation (5). In other words: the simulation iterates equation (1) using the GHG value estimates of the previous stage on the right-hand side, tracking the process where in each round, all producers use the best information available to them, i.e. the accurate BoM vector and, for all inputs, the estimate of GHG values from the previous round. This presupposes that the GHG value calculations of input producers are made available to the users of inputs.

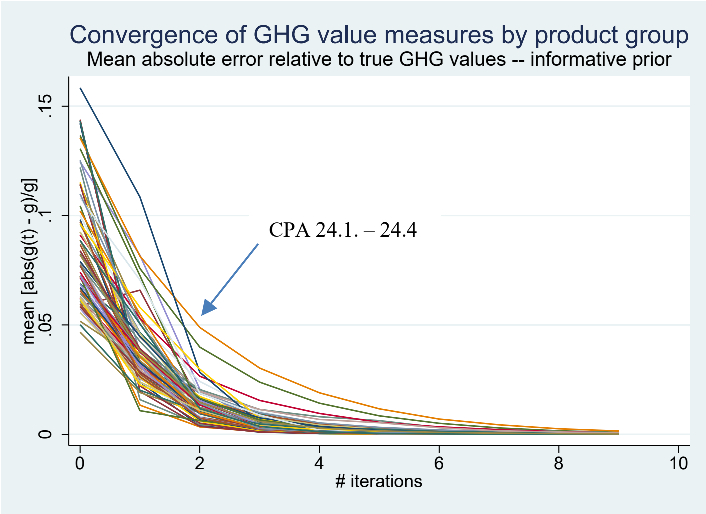
Column 11 shows the initial distance from equilibrium by sector, as given by the mean absolute difference to the true E-liabilities. Column 12 and 13 depict the state of the social learning process after three and five iterations. Graph 4 gives, for all product groups, a graphic representation of learning in iterations 1 to 10, depicting the mean absolute

[20] For consistency, these have been taken from the IO tables for 2015 based on the national accounts revision in 2014, not the revision in 2019. Destatis (2018a) does not provide euro values of final use.

[21] The different reference years mean that neither the quantity structure of output nor the price indices are consistent, and the production technology as given by the input coefficients also varies. Furthermore, Destatis (2018) measures carbon content and not the content of CO_2 equivalents. In the case of agriculture, this makes a huge difference. Most importantly, Destatis (2018) uses specific measures for the carbon content of import goods, while the computation in this simulation exercise relies on the assumption that the technology of imports and of national production are identical.

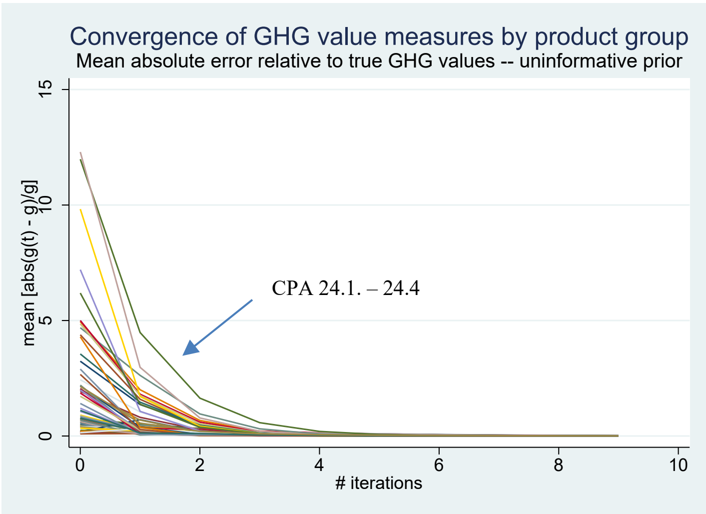
distance of estimates $g_k \big|_i$ from the true E-liabilities g_k, normalised by the level of E-liability.

Graph 4: GHG value learning using sectoral GHG contents as initial value



Convergence is very fast for almost all products. A major exception is product group 19, CPA 24.1.-24.4, *Basic iron and steel, products of the first processing of steel*, where convergence is visibly slower. This is related to a large input coefficient of 0.5 for inputs of goods of the same sector. With this, a "wrong" prior set of E-liabilities will be transmitted with a relatively high weight to the next iteration of the learning process.

Graph 5: GHG value learning using uninformative prior – overall average



Whereas Graph 4 may be said to capture social learning for *rather informative* starting values, the true GHG content at the group level, Graph 5 repeats the simulation with what might be called the *most uninformative possible* set of initial values: a uniform value equal to overall average GHG content. Initial distances are much higher, by about a factor of 10, but even so, the estimates are rather accurate after the fourth iteration, except for CPA 24.1-24.4 mentioned above.

In the relationship between product-level outcomes and group-level outcomes, there is a potential aggregation bias. The Leontief matrix is a non-linear transformation of the original input coefficients, thus the group averages of GHG values at the product level may not correspond exactly to the result of computing carbon content at the group level. In the simulation, the aggregation bias did not have any visible impact.

6 Is there scope for voluntary disclosure?

To a certain extent, GHG value disclosure may rely on voluntary action by producers. The existence of the GHG Protocol and its increasing use shows that there is a distinct commercial interest in obtaining and communicating carbon accounting information; see Annex 3. In 2016, according to the GHG Protocol website, 92% of the Fortune 500 enterprises that responded to a survey on carbon disclosure were running programmes based on GHG Protocol standards. Another non-profit entity, CDP (formerly the Carbon Disclosure Project), disseminates a standardised questionnaire on GHG activities. More than 2,000 companies worldwide provide answers on a voluntary basis, which are made available to the public and used as inputs in commercial databases.

It is also clear that some firms have good reasons to declare the GHG value of their products either incorrectly or not at all. Just as with financial costs, if there is an opportunity to make products look cheaper than they really are or to avoid talking about costs altogether, some market participants will take it.

To establish a GHG value system, some reporting obligations will be necessary. This section makes the argument that reporting obligations may not have to be broad-based. Instead, legislation only needs to make sure that a threshold volume of disclosure, e.g. from large companies, is surpassed. *Under certain conditions, this will trigger a process that will end in almost universal voluntary disclosure.*

In principle, it is not in the interest of producers that subscribe to the GHG value system to conceal the GHG content of their output if an E-liability system is used as a direct communication device – if they choose not to declare the E-liability of their output, they will not get the credit. External auditing is needed to make sure that GHG debits and credits match inventory changes. In addition, basic valuation standards need to be backed up. Producers may rig the valuation of inputs that have no GHG values attached. By distorting the allocation, they can make their output look "too cheap" in terms of GHG or cross-subsidise one product line with GHG-sensitive demand by charging other product lines where demand is inelastic. Thus, as a first component, *formal auditing* needs to make sure that the GHG value measure is a fair estimate, using the information on direct emissions and production interlinkages existing at the company level. Auditing is carried out against disclosure standards that have to be specified in advance. It is best organised in parallel with financial auditing, with governments having the right to scrutinise dubious statements. In this respect, it is promising that the IFRS is about to change its statutes in order to set up a board on disclosing standards for environmental information.

Second, an *information platform* is required that makes accessible the information available on:

- industry averages;
- direct emissions from company reports;
- GHG value estimates, as far as they exist.

There is a path that leads to voluntary disclosure by (almost) all firms. Suppose that the information platform, in addition to making existing information publicly available, computes estimated average GHG content for firms of a given industry that do not disclose their E-liabilities – from the known industry averages and the known E-liabilities of the firms that do disclose. These estimates will be used to evaluate the average E-liabilities of inputs produced by non-disclosing firms.

Producers with low GHG values, relative to their peer group, will have a clear incentive to disclose, especially if they are active in GHG-sensitive markets. With low GHG values, they can charge higher prices to their buyers of intermediate or final goods or reap the rewards of positive publicity. This fact will generate a signal value for the decision not to disclose. The signal will be reinforced by calculating sector averages for GHG values conditional on not disclosing. With many companies disclosing, those that do not disclose will look increasingly unattractive. We may envisage an iterative process where first the cleanest firms disclose, then those that are not top tier, but still well above average, etc. In the end, the only firms to not disclose will be those with rather extreme GHG values, and the fact that they do not disclose will be informative enough.

This process of unravelling due to using the industry average as a proxy for non-disclosing firms is quite similar to the Stiglitz and Weiss (1981) account of the possible breakdown of the credit market under asymmetric information. In the scenario at hand, however, the result is a separating equilibrium with voluntary disclosure. In order to create an incentive that is great enough to trigger this mechanism on a large scale, we may need to overcome a threshold number of participating firms.[22]

Result 4: *Given a sufficient degree of competitive pressure, an equilibrium with voluntary disclosure will result if:*

1. *firms are audited according to predefined disclosure standards;*
2. *sector-level information and the disclosed GHG values are made publicly available; and*
3. *carbon intensity estimates based on the unaccounted-for parts of industry totals are disseminated to be used for firms that do not disclose.*

Similar to the diffusion of information via the price system, information on carbon usage can be processed in a decentralised and efficient manner, even without any formal reporting obligation. The key ingredients are micro-level auditing and a centralised information platform. This is where central banks may have an important role to play. They need to collect much of the required information anyway in order to classify their assets and collateral and, in some important cases, to rate companies. In addition, they have the mandate to disseminate statistical information for policy purposes as well as all the necessary infrastructure, experience and working routines.

One obvious challenge is imports. Exporters may not have the same incentives to disclose if their markets are located largely outside a country that implements a system of GHG value indicators. Many large international companies disclose their carbon usage data voluntarily, and the upcoming EU legislation on the carbon border adjustment mechanism will further expand the information available on emissions. Still, for many products and companies, the information will likely be missing permanently. For those products and firms, industry averages specific to the exporting country can be used. For the case of Germany, see Destatis (2019) for a tabulation of the carbon content of imports from major trading partners by industry in 2013 to 2015. Alternatively, one can find reference producers in the home country. It is clear that the problem will be less acute if countries within a large economic zone such as the European Union act in unison.

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[22] Some enterprises are already reporting the GHG content for their products today. In 2019, a Swedish company producing oat-based dairy alternatives gathered more than 57,000 signatures for its petition to the Deutsche Bundestag, the German Federal Parliament, to make GHG content disclosure obligatory for retail food. Given the size of the petition, there was a public hearing. There is also a market for consultancies that help compute product-specific carbon content. Competitive pressure will increase considerably once reporting carbon content becomes commonplace and accountants offer standardised and cheap solutions.

7 Policy perspectives

At the heart of sustainable finance is the idea that investors need to distinguish between aligned and non-aligned projects, between firms with a higher or a lower environmental risk, and between portfolios with a higher or lower carbon footprint. The information needed to make this type of distinction is granular by necessity, i.e. firm level or product level. GHG values make it possible to evaluate whether a firm's output portfolio is sustainable. If the GHG values of its products are higher than the GHG values of similar products, chances are high that the firm will not be viable if the environmental cost of production is duly taken into account. More generally, if the GHG value of a firm's output is high compared with that of others (similar or not), it can be expected that the growth potential of this business model is limited. High GHG values therefore reflect an elevated market risk. GHG values of products are an ideal tax base. Like a VAT, such a tax should be levied on final use, otherwise the emissions in the production of intermediate products would be taxed several times.

Currently, there is much to be done and, by consequence, there is much that can still be achieved. Annex 3 describes two strands of current and upcoming EU legislature. The draft CSRD, which is currently a rather empty legislative shell, will soon be fleshed out with concrete reporting requirements. The Taxonomy Regulation and its associated delegated acts are aimed at distinguishing firms that are aligned to environmental transition goals from those that are not, and this policy will need a firm foundation. Apart from these two strands, the "Fit for 55" legislative package sets out new reporting requirements for key activities, and it enlarges the scope for emissions trading considerably.[23] The European Banking Authority (EBA) is discussing a framework for prudential disclosures on ESG risks that would force banks to report on their engagement with counterparties that are among the most carbon-intensive in the world, be it in the European Union or in the home country of the institution.[24] The IFRS Foundation is overhauling its statutes to set up a board for sustainability-related reporting. Politically, the need for a coherent and relevant indicator system such as GHG values is obvious.

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[23] For an overview on the entire "Fit for 55" package, see the official communication. There will be separate emissions trading systems (ETSs) for buildings and road transport, and the existing ETS will cover maritime transport. The ETS is important for data availability as it creates a need for careful accounting. Here is a link to the proposed Directive.

[24] See the Consultation Paper Draft Implementing Standards on prudential disclosures on ESG risks in accordance with Article 449a CRR, especially paragraphs 40-42 and the corresponding annexes.

In discussing information requirements and implementation, this paper has implicitly described some of the policy options for central banks and international organisations to support the evolution of a broad-based and consistent system of GHG indicators. The following is a list of policy options resulting from the discussion above:

1. Cooperate with Eurostat and the NSIs in setting up a *rather disaggregated EEIO model* for the euro area, and also for some of the larger countries within it if this is warranted by observed heterogeneity. This would be very effective in creating a joint framework for condensing data at a sectoral level.[25]
2. Set up and maintain a *dissemination platform for GHG content and GHG content data* at the level of sectors, enterprises and products. Disclosure standards may oblige producers to use GHG data published on that platform for their inputs. These platforms may also name and make available reference proxies for cases where product-level information is not available, especially in the case of imports.
3. Develop and propagate *disclosure standards* and assist in setting them as a basis for comparability and auditing. Those rules can build on the relevant GHG Protocol standards, at least for direct emissions.[26] What inputs to consider and how to evaluate them needs to be determined. In this context, it is necessary to make concrete decisions on the options in Scope 3 accounting relating to practicability and informational content. The organisations that support the GHG Protocol, namely the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), may have a leading role to play here. There are also ISO standards that bear a strong resemblance to the corresponding GHG Protocol standards.[27]
4. Interact with the European Commission and possibly also with the IFRS on potential *disclosure requirements,* especially regarding the CSRD (see Annex 3). In light of the discussion above, possible disclosure requirements should target large companies so as to overcome a threshold that will induce voluntary disclosure by others, and by producers of primary goods and import goods so as

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[25] It matches Recommendation 1 in the suggested work plan for the G20 Data Gaps initiative.

[26] See, in particular, WRI and WBCSD (2004) as a standard for Scope 1 and 2 emissions, WRI and WBCSD (2011a) for Scope 3 emissions at the enterprise level, WRI and WBCSD (2011b) for corresponding standards for Scope 3 emissions at the product level, and the Technical Guide on Scope 3 emissions in WRI and WBCSD (2013).

[27] See specifically ISO 14064-1:2018 on GHG reporting at the organisation level and ISO 14067:2018 on reporting at the product level.

to ensure valid E-liabilities at the front end of the value chain.[28] It would be helpful if financial and environmental disclosure auditing could be carried out in synchronicity.

These are largely the same options that are available with respect to any other meaningful system of indicators, but the GHG value system is adept at showing how these policy measures fit together and how they interact.

A simplified solution would aim to induce producers to disclose GHG values for a targeted subset of products only, such as energy, transportation, agriculture and parts of the manufacturing sector; see Graph 2 for an overview. This is easier to initiate, but the simplicity comes at a cost. For many input goods, GHG value coefficients will have to be imputed permanently, as even in the long run there will be no values from input providers. Result 3 would hold only conditionally. Even then, though, valuable granular information would come from producers using their private knowledge on the input composition. This is perhaps the most important feature of a system of GHG values.

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[28] As already mentioned, the upcoming legislation on the carbon border adjustment mechanism and the enhancement of the scope of the carbon emissions trading systems are beneficial in this respect.

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Annex 1: GHG values – Group-level data for Germany (2018) and product-level simulation

			Group-level data and computations				Product-level simulation			Structure of GHG values, group av.			GHG value learning: Av. absolute error[3]		
#	CPA	Product groups[1]	Total use, incl. imports (€ bn)	Total use, nat. prod. (€ bn)	Dir. em. (t CO_2 equiv.)[2]	GHG content (kg/€)	# prod. in sim.	Average GHG value	St. dev. GHG value	Scope 1 emiss. intens.	Scope 2 emiss. intens.	Scope 2 + upstr. Scope 3	1st it.	3rd it.	5th it.
1	01	Products of agriculture, hunting and related services	84 920	52 313	72 368	1.942	85	1.893	0.324	1.3455	0.0714	0.54787	0.2568	0.0076	0.0006
2	02	Products of forestry, logging and related services	7 097	6 205	482	0.285	7	0.279	0.019	0.0747	0.0067	0.20384	0.0157	0.0041	0.0002
3	03	Fish and other fishing products; aquaculture products; support services	1 300	483	195	0.678	1	0.757		0.4654	0.0664	0.29117	0.0790	0.0074	0.0003
4	05	Coal and lignite	7 887	2 930	2 359	1.241	8	1.277	0.141	0.8653	0.2188	0.41133	0.0977	0.0042	0.0008
5	06	Crude petroleum and natural gas	66 860	1 474	1 202	1.107	67	1.080	0.152	0.7843	0.138	0.29617	0.1253	0.0047	0.0012
6	07-09	Metal ores, mining and quarrying products, support services	23 152	14 197	923	0.475	23	0.479	0.041	0.0655	0.128	0.4133	0.0344	0.0077	0.0007
7	10-12	Food, beverages, tobacco products	255 527	194 697	9 882	0.768	256	0.748	0.114	0.0518	0.0415	0.69606	0.0902	0.0153	0.0008
8	13-15	Textiles, wearing apparel, leather and related prducts	85 333	24 005	920	0.356	85	0.362	0.033	0.0378	0.0648	0.3238	0.0267	0.0050	0.0010
9	16	Wood and of products of wood and cork, except furniture	33 622	25 733	6 952	0.664	34	0.668	0.091	0.2698	0.055	0.39851	0.0614	0.0082	0.0014
10	17	Paper and paper products	61 570	44 214	9 753	0.776	62	0.806	0.101	0.226	0.1327	0.57956	0.0790	0.0156	0.0024
11	18	Printing and recording services	18 207	17 352	629	0.331	18	0.327	0.029	0.0338	0.0524	0.29319	0.0222	0.0061	0.0012
12	19	Coke and refined petroleum products	96 161	58 363	27 603	1.501	96	1.519	0.216	0.4966	0.0859	1.02256	0.1712	0.0141	0.0017
13	20	Chemicals and chemical products	265 327	164 842	24 765	0.674	265	0.678	0.084	0.1527	0.0774	0.5256	0.0634	0.0140	0.0029
14	21	Pharmaceutical products and preparations	88 597	39 241	1 779	0.263	89	0.269	0.027	0.0459	0.0045	0.22296	0.0200	0.0048	0.0011
15	22	Rubber and plastic products	114 640	79 729	2 544	0.429	115	0.434	0.060	0.0329	0.0815	0.40132	0.0443	0.0109	0.0022
16	23.1	Glass and glass products	16 034	10 645	4 627	0.849	16	0.833	0.100	0.4238	0.1407	0.40917	0.0788	0.0055	0.0010
17	23.2-23.9	Ceramic products, processed stone and clay	45 580	38 289	36 672	1.477	46	1.456	0.240	0.9353	0.127	0.52089	0.2028	0.0053	0.0006
18	24.1-24.3	Basic iron and steel, products of the first processing of steel	123 212	91 387	38 090	1.633	123	1.610	0.270	0.4232	0.1039	1.18706	0.2132	0.0668	0.0239
19	24.4	Basic precious and other non-ferrous metals	78 447	42 957	3 285	0.706	78	0.700	0.114	0.0802	0.095	0.61958	0.0914	0.0343	0.0134
20	24.5	Casting services of metals	19 435	19 215	1 898	0.694	19	0.704	0.061	0.0994	0.1486	0.60476	0.0442	0.0148	0.0057
21	25	Fabricated metal products, except machinery and equipment	171 347	138 197	3 199	0.383	171	0.384	0.044	0.0229	0.0508	0.3616	0.0353	0.0104	0.0038
22	26	Computer, electronic and optical products	204 376	78 182	1 118	0.193	204	0.192	0.014	0.0143	0.026	0.17784	0.0109	0.0020	0.0004
23	27	Electrical equipment	164 100	97 212	931	0.210	164	0.211	0.015	0.0097	0.024	0.20149	0.0119	0.0034	0.0009
24	28	Machinery and equipment n.e.c.	340 119	247 265	2 439	0.247	340	0.246	0.020	0.0099	0.0248	0.23657	0.0162	0.0039	0.0012
25	29	Motor vehicles, trailers and semi-trailers	526 272	399 656	3 913	0.260	526	0.258	0.026	0.0099	0.0169	0.2477	0.0213	0.0048	0.0014
26	30	Other transport equipment	77 636	50 045	416	0.246	78	0.251	0.022	0.0083	0.0155	0.24263	0.0185	0.0040	0.0008
27	31-32	Furniture and other manufactured goods	96 159	54 396	1 461	0.225	96	0.224	0.013	0.0259	0.0202	0.19825	0.0105	0.0022	0.0005
28	33	Repair and installation services of machinery and equipment	58 703	54 951	226	0.246	59	0.245	0.018	0.0039	0.0192	0.24152	0.0145	0.0049	0.0017
29	35.1, 35.3	Electricity, distribution services for electricity and air conditioning	121 115	117 816	354 877	4.210	121	4.290	0.617	3.0536	0.9997	1.23616	0.4951	0.0254	0.0016
30	35.2	Manufactured gas; distribution services of gaseous fuels through mains	15 338	15 338	3 181	0.664	15	0.666	0.056	0.2171	0.1761	0.44848	0.0472	0.0055	0.0007
31	36	Natural water; water treatment and supply services	11 223	11 223	79	0.469	11	0.480	0.103	0.0079	0.4168	0.47248	0.0762	0.0129	0.0006
32	37-39	Sewerage, waste, materials recovery, remediation services	72 482	62 897	20 406	0.482	72	0.486	0.072	0.3278	0	0.15823	0.0556	0.0024	0.0002
33	41	Buildings and building construction works	74 952	74 619	2 536	0.336	75	0.329	0.053	0.0339	0.0159	0.29531	0.0422	0.0037	0.0005
34	42	Constructions and construction works for civil engineering	48 297	48 082	1 634	0.339	48	0.335	0.041	0.034	0	0.3008	0.0335	0.0042	0.0008
35	43	Specialised construction works	233 498	232 425	6 225	0.235	233	0.236	0.019	0.0271	0.009	0.20871	0.0151	0.0024	0.0005
36	45	Wholesale and retail trade and repair services of motor vehicles and motorcycles	102 421	93 337	1 645	0.138	102	0.139	0.013	0.0177	0.0424	0.1215	0.0103	0.0016	0.0003
37	46	Wholesale trade services, except of motor vehicles and motorcycles	295 055	290 252	7 671	0.180	295	0.181	0.016	0.0261	0.0305	0.15485	0.0124	0.0021	0.0003

38	47	Retail trade services, except of motor vehicles and motorcycles	208 270	208 270	8 550	0.209	208	0.213	0.026	0.041	0.0856	0.17167	0.0202	0.0027	0.0003
39	49	Land transport services and transport services via pipelines	120 777	109 344	18 024	0.404	121	0.407	0.050	0.161	0.098	0.24596	0.0397	0.0040	0.0004
40	50	Water transport services	31 930	24 585	40 672	2.576	32	2.506	0.344	1.6325	0	0.87373	0.2974	0.0269	0.0022
41	51	Air transport services	30 996	25 066	30 802	1.848	31	1.793	0.293	1.1641	0.0015	0.62914	0.2386	0.0170	0.0012
42	52	Warehousing and support services for transportation	159 252	143 203	10 679	0.280	159	0.287	0.032	0.077	0.017	0.20967	0.0258	0.0036	0.0005
43	53	Postal and courier services	53 936	53 564	4 738	0.292	54	0.295	0.030	0.0868	0.0394	0.2082	0.0235	0.0021	0.0004
44	55-56	Accommodation, food and beverage serving services	122 744	103 984	3 112	0.299	123	0.299	0.035	0.0292	0.0878	0.26996	0.0286	0.0091	0.0005
45	58	Publishing services	65 713	47 335	*234*	0.116	66	0.116	0.008	0.0051	0.0182	0.11053	0.0066	0.0016	0.0003
46	59-60	Film, video, TV production, sound recording, music publishing; broadcasting	41 781	37 769	*187*	0.095	42	0.094	0.009	0.0051	0.019	0.08893	0.0074	0.0015	0.0003
47	61	Telecommunications services	73 151	68 822	*341*	0.138	73	0.136	0.014	0.0049	0.0456	0.13125	0.0113	0.0020	0.0002
48	62-63	IT and information services	177 969	156 794	*776*	0.031	178	0.031	0.003	0.005	0.0063	0.02577	0.0026	0.0005	0.0001
49	64	Financial services, except insurance and pension funding	152 078	141 693	969	0.067	152	0.067	0.006	0.006	0.0177	0.06096	0.0045	0.0007	0.0001
50	65	Insurance and pension funding services, except compulsory social security	83 840	79 574	1 634	0.068	84	0.070	0.005	0.0059	0.0121	0.06402	0.0043	0.0009	0.0002
51	66	Services auxiliary to financial services and insurance services	38 780	35 403	7 900	0.065	39	0.066	0.005	0.0061	0.0151	0.06016	0.0042	0.0008	0.0001
52	68	Real estate services	458 374	457 497	591	0.048	458	0.049	0.005	0.0013	0.0094	0.04736	0.0037	0.0008	0.0001
53	69-70	Legal and accounting services; services of head offices; management consulting	188 901	172 465	1 730	0.067	189	0.068	0.005	0.0098	0.0115	0.05811	0.0040	0.0007	0.0001
54	71	Architectural and engineering services; technical testing and analysis services	89 789	80 922	812	0.072	90	0.074	0.005	0.0106	0.0125	0.06326	0.0045	0.0006	0.0001
55	72	Scientific research and development services	130 529	110 196	1 105	0.102	131	0.102	0.009	0.0096	0.0359	0.09263	0.0075	0.0010	0.0001
56	73	Advertising and market research services	35 434	25 858	344	0.087	35	0.087	0.006	0.0107	0.0115	0.07642	0.0044	0.0009	0.0002
57	74-75	Other professional, scientific, technical and veterinary services	36 358	34 287	259	0.130	36	0.131	0.009	0.0099	0.0362	0.12154	0.0068	0.0016	0.0002
58	77	Rental and leasing services	97 801	86 320	354	0.030	98	0.030	0.002	0.0041	0.006	0.02581	0.0019	0.0003	0.0001
59	78	Employment services	40 378	37 799	155	0.038	40	0.037	0.003	0.004	0.0029	0.0327	0.0022	0.0004	0.0001
60	79	Travel agency, tour operator and other reservation services and related services	37 438	35 773	147	0.458	37	0.468	0.065	0.0042	0.0087	0.46332	0.0520	0.0086	0.0009
61	80-82	Security, buildings and landscape, office administrative and support services	139 834	131 405	540	0.123	140	0.126	0.010	0.0041	0.0277	0.12166	0.0086	0.0013	0.0002
62	84.1-84.2	Public administration and defence services	255 069	254 071	5 002	0.130	255	0.130	0.009	0.0198	0.0291	0.11013	0.0075	0.0013	0.0001
63	84.3	Compulsory social security services	36 005	36 005	709	0.055	36	0.055	0.006	0.0196	0.0028	0.03585	0.0041	0.0003	0.0001
64	85	Education services	176 224	176 042	3 209	0.075	176	0.075	0.007	0.0182	0.0203	0.05707	0.0055	0.0008	0.0001
65	86	Human health services	236 073	236 038	2 213	0.124	236	0.125	0.012	0.0184	0.0399	0.10616	0.0097	0.0018	0.0001
66	87-88	Residential care and social work services	106 200	106 200	1 772	0.134	106	0.132	0.012	0.0192	0.0413	0.11326	0.0095	0.0018	0.0001
67	90-92	Arts, culture, entertainment and gambling	38 182	34 577	1 349	0.130	38	0.133	0.013	0.0398	0.0338	0.09344	0.0099	0.0010	0.0001
68	93	Sporting services and amusement and recreation services	29 786	29 649	1 157	0.147	30	0.146	0.012	0.0403	0.0372	0.106	0.0090	0.0016	0.0002
69	94	Services furnished by membership organisations	43 670	43 482	1 697	0.110	44	0.109	0.010	0.0379	0.0199	0.07085	0.0082	0.0008	0.0001
70	95	Repair services of computers and personal and household goods	4 626	4 366	170	0.157	5	0.167	0.023	0.0375	0.0499	0.12909	0.0187	0.0025	0.0002
71	96	Other personal services	53 532	53 532	2 089	0.185	54	0.190	0.022	0.0387	0.0725	0.15101	0.0174	0.0022	0.0002
		Total[4)]	**7 701 421**	**6 376 054**	**812 911**	**0.399**	**7 699**	**0.3953**	**0.6387**	**0.1336**	**0.0531**	**0.2617**	**0.0406**	**0.0059**	**0.0012**

Source: Destatis (2021a) for sectoral aggregates and input-output coefficients, Destatis (2021b) for direct emissions of CO_2 equivalents, author's computations.

1) A group "Services of hh. as empl. of dom. personnel a.o. services prod. by priv. hh." has not included into calculation, as it has no prod. interlinkages with other groups. Thus total use differs slightly from published values.

2) Direct emissions for the following product groups have been estimated by splitting up larger cells in Destatis (2021) emission statistics according to their weight in total use: 33-34, 45-48, 49-51, 53-57, 58-61, 62-63 65-66, and 67-71. Direct emission intensities in those subgroups thus are identical by assumption.

3) GHG value learning computed using an informative initial value (group-level averages); see Sect. 5.2.

4) Group-level GHG value average computed using weights from total use including imports. This average cannot be used for calculating carbon contents of final use.

Annex 2: IO models useful for generating proxy GHG values

It is argued in Section 4.1. that the total emission intensity of a sector, as calculated from an IO data base, can be used as a sector-level proxy for input GHG values on the right-hand side of equation (1) if product-level information is missing. This Annex looks more closely at IO models as a source for emissions data.[29]

The System of Environmental Economic Accounting (SEEA) is a multipurpose conceptual framework that describes the interactions between the economy and the environment, and the stocks and changes in stocks of environmental assets. It is a satellite account of the System of National Accounts (SNA) and uses definitions of sectors, industries, time and space consistent with the National Accounts. The framework is a United Nations system. Many countries, including Germany, maintain reporting systems that conform to SEEA standards. In the following, we refer to the SEEA Central Framework adopted in 2012 in United Nations (2014). The SEEA is divided into three areas. First, the *physical flow accounts* describe flows of material between the environment and the economy and its sectors and industries, very much in the same way as flows of goods and services and funds are described in the SNA. Additionally, the *environmental activity accounts* identify economic transactions within the SNA that may be considered environmental, such as environmental protection. Finally, the *asset accounts* focus on the recording of stocks and flows associated with environmental resources of many kinds. For the purpose of this analysis, it is the physical flow accounts that are relevant.

These accounts depict the flow of designated substances from the environment to the economy and its sectors and industries, and vice versa – among them, of course, carbon dioxide and other greenhouse gases. Importantly, the accounts are disaggregated by industry in a way that is consistent with the supply and use tables and standard IO tables as part of the National Accounts. In the first level of analysis, the direct emissions of industries are recorded. This makes it possible to look at the emissions of industries and compare them against, for example, their value added. This gives us a first impression of the carbon impact of industries, not just in terms of absolute size, but also in terms of intensity. Second, using the machinery of supply and use tables and IO analysis, it is possible to calculate the carbon impact of *final demand as well as of its components* – consumption, investment, imports and exports by industry. This calculation fully reflects

[29]See footnote 6 and Section 4.1 for references to IO models for industrial ecology.

the industry interlinkages that are discussed above, using the same analytical apparatus. The matrix of industry interlinkages used in IO analysis corresponds to the matrix $\mathbf{A}$ in Section 2, albeit at an industry level. This is of high analytical value: the direct carbon emissions of electricity production may be of interest in and of themselves, but to the degree that electricity feeds as an input into the production of other goods of final demand, the emissions need to be attributed to these goods. As an example, in Destatis (2019), Tables 2.1.1. and 3.1.1. show the carbon content of final demand in Germany for 2008 to 2015, in total and for 49 industries and product groups. Similar tabulations exist for the final demand components import, export, consumption and investment separately. The publication also gives estimates of carbon content by industry for imports from all major trading partner countries. [30]

The OECD Inter-Country Input-Output (ICIO) tables are the basis for the Trade-in-Value-Added (TiVA) project. They have been successfully employed to compute the carbon content employed in final demand and in international trade; see Wiebe und Yamano (2016) and Yamano and Guilhoto (2020). Partly building on the ICIO tables, Eurostat has made accessible a new database known as Full International and Global Account for Research in Input-Output Analysis (FIGARO).[31] Since May 2021, the FIGARO tables have been part of the annual production process. They link data on national accounts, business, trade and labour markets for the EU Member States and their main trading partners. The relationship between the EU countries, the United Kingdom and the United States are depicted at a level of 64 industries. For the remaining EU partner countries, the data come from the OECD ICIO and cover 30 industries. IO tables are notorious for their long publication lag. Using nowcast methods, FIGARO tables are published with a lag of only two years, i.e. in 2022, tables for 2020 will be available. The data for the two most recent years are at a higher level of aggregation than the rest.

Beyond official statistics, there are environmentally extended IO (EEIO) models for academic and commercial research that can be used for analysing emissions. They collect information on the physical flows of goods and services from official and private sources and combine them with estimates to get a more disaggregated picture. EXIOBASE is an academic endeavour. The hybrid version of the multiregional model EXIOBASE 3 is based on physical, not monetary units. The database features 43 countries, 5 rest of world regions, 200 products, 164 industries, 39 resources, 5 land categories and 66 emissions.

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[30] See Section 5.2 for further information.

[31] See the FIGARO website and Remond-Tiedrez and Rueda-Cantuche (2019). To the knowledge of the author, FIGARO has not yet been used to compute emission intensities.

EXIOBASE 2015 was used by Smets, Schellekens, Bauwens und Wilting (2021). The time series of the hybrid version only extends to 2011. A somewhat smaller multi-country alternative is the World Input-Output Database (WIOD), financed by the European Commission and updated to 2014 in its 2016 release. WIOD features 56 sectors and covers 40 countries, including all 27 EU Member States as of 2007, plus 1 rest of world region. The environmental accounts were updated to 2016. See Timmer et al. (2015) for a description and Corsatea et al. (2019) for the update of environmental accounts data. Lastly, the EEIO model of Trucost, an environmental consulting agency affiliated to S&P, is based on supply and use tables from the United States Bureau of Economic Analysis. Enriching these with additional breakdowns, Trucost arrives at an EEIO model with no less than 464 sectors.[32] The model helps to estimate firm-level emission intensities; see Section 5 for more information on these data.

This Annex may be the place to reflect on how IO models could be made more informative and useful for classification purposes. One major issue is sectoral distinctions. Obviously, more is better, as long as the distinctions can be supported by high quality and timely data. But with limited resources, choices have to be made.

1) Sectoral distinctions should obviously be more granular in areas where heterogeneity is large. Agricultural output, for example, has high average GHG content, but this content depends strongly on the composition of the output, such as the production of cattle or poultry. In those cases, different product groups should be considered separately. Generally, distinctions will be informative in broad areas where GHG intensity is high – electricity, transportation, agriculture, and a number of manufacturing sectors. In service industries such as financial services, insurance, and consulting, GHG intensities are low and rather homogeneous, coming from the use of computers, the heating of office buildings and travel. It is thus reasonable to treat these in a broader fashion than the first group.
2) Distinctions based on production technology would be significant and informative. Electricity from coal, for example, has high GHG intensity, and electricity from solar panels does not. If statisticians can make this distinction and clarify who uses what sort of electric power, this could have a large influence on the estimated GHG content of other product groups. Some forms of agriculture

[32] See Trucost (2020). While this is an impressive figure, the issue of whether it is appropriate to use US-based intensities for companies all over the world, even in countries that are far from the technological frontier, is up for debate.

are clearly more GHG-intensive than others due to the use of fertilisers. For climate mitigation, the proper objective cannot be to avoid the production of carbon-intensive goods altogether. Electricity and agricultural output will always be needed. Rather, society needs to make sure that GHG intensities are properly taken into account on the demand side and that the production that does take place is carried out in a carbon-efficient way. Unfortunately, IO models typically do not distinguish between products based on their technology.

3) In a similar vein, there may be big differences between formal, large-scale types of production, e.g. by multinational firms, and informal, small-scale, purely national types of production. This distinction may be of specific importance in developing countries.

On a different note, IO models and statistics are more useful for environmental purposes if they are physical, or at least hybrid. This means that direct emissions or electricity use can then be traced back to physical production activities, not just to financial flows. The analysis also needs to be timely to be relevant. More resources and some nowcasting, as in FIGARO, may help a lot.

Lastly, it is important that the analysis be international. For the simulation reported in Section 5, in order to obtain useful initial values, the author simply assumes that imports are produced by the technology used in national production, as reflected in the input coefficients of national production. In practice, this would be misleading and would mask important distinctions that can and should be made, e.g. when dealing with carbon leakage. Thus, existing large-scale international IO models are a good starting point.

Annex 3: Microdata on emissions – availability today and upcoming EU disclosure requirements

1. Voluntary disclosure

Today, the disclosure of carbon emissions is largely voluntary. In 2001 (revised in 2004), the *GHG Protocol* published standards that are being followed by a growing number of large companies. The GHG Protocol is maintained and supported by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The latter is an association of private enterprises that is committed exclusively to the topics of economics and sustainability. The GHG Protocol defined three scopes for carbon accounting purposes:[33]

- *Scope 1* – Direct GHG emissions: Direct GHG emissions from sources that are owned or controlled by the company.
- *Scope 2* – Electricity (indirect GHG emissions): GHG emissions from the generation of purchased electricity consumed by the company.
- *Scope 3* – Other indirect GHG emissions: Scope 3 is an optional reporting category in the GHG Protocol that allows for the treatment of all other indirect emissions, upstream or downstream. These are a consequence of the activities of the company, but stem from sources not owned or controlled by the company, such as extraction and production of purchased materials, transportation of purchased fuels, and use of sold products and services.

Disclosures of Scope 1 and 2 emissions are binding under the standard. On top of this, the GHG Protocol has issued detailed recommendations regarding Scope 3 emissions, which are optional under the standard; see footnote 9 and the sources cited therein.

As the number of voluntary disclosures grows, platforms have emerged that make those disclosures available to the public. *CDP* (formerly the Carbon Disclosure Project) was founded in 2000 and has evolved into a large and comprehensive database on environmental matters. According to Wikipedia, 2,400 companies worldwide, and 82% of Fortune 500 companies, reported their GHG emissions to CDP in 2009. Most of the disclosing companies follow GHG Protocol standards: in 2016, 92% of the Fortune 500

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[33] See WRI and WBCSD (2004), Chapter 4 “Setting operational boundaries”.

enterprises that responded to the CDP survey were running programmes based on the GHG Protocol.[34]

CDP data are being sold to firms and universities (at a heavy discount) and form the backbone of what is available from *commercial databases***,** among them Trucost and ISS ESG.[35] These companies also collect disclosures directly from websites or non-financial statements and augment them with approximations and estimates to generate a broad information base for their clients, namely institutional investors.

It is interesting to see that 89.1% of the Scope 1 data reported by Trucost as collected from companies originate from CDP. There is thus a clearly visible line running from GHG Protocol standards and via voluntary disclosures by large companies through CDP or non-financial statements through to commercial companies trying to fill data gaps to serve the needs of investors for a wide range of firms. There is readiness to disclose on the one side and there is market demand on the other. Data quality, however, is a big issue if company reports are not standardised and much of the total needs to be estimated using proprietary and partly undisclosed techniques. For investors, it is not easy to use this information to make proper distinctions at the company level. For policymakers, it is impossible.

2. Upcoming disclosure requirements

The current EU legislature on environmental disclosure is moving forwards on two fronts: the Taxonomy Regulation track and the Non-Financial Reporting Directive track.

Taxonomy Regulation 2020/852[36] of 18 June 2020 is designed to establish a framework for facilitating sustainable investment. Article 8 of the Regulation obliges non-financial firms to disclose the proportion of their activity (in terms of turnover) that is aligned to environmental purposes under this taxonomy in order to develop criteria for whether certain investment qualify as sustainable or not. In material terms, Article 8(4) refers to associated regulations (delegated acts) that are to be adopted separately. These are commonly known as “Article 8 delegated acts”:

- The *Disclosure Delegated Act of 6 July 2021* further specifies the disclosure obligations under Article 8 of the Taxonomy Regulation. It obliges non-financial and

[34] GHG Protocol website, 14 August 2021.

[35] Trucost is an affiliate of S&P Global. For more information on Trucost environmental data, see Section 5. ISS ESG is a consulting company owned by Deutsche Börse.

[36] Links to all Taxonomy Regulation legislation and important metadata can be found on a dedicated European Commission webpage.

financial undertakings to disclose in non-financial statements what parts of their activities are aligned to certain environmental goals. The Act defines key performance indicators (KPIs) in terms of turnover, capital expenditure and operational expenditure. It has five annexes.

- The taxonomy that classifies what activities are "aligned" is described separately in two annexes of the *EU Taxonomy Climate Delegated Act of 4 June 2021.* These annexes introduce technical screening criteria for two of the six environmental objectives specified in the Taxonomy Regulation. They determine the conditions under which an economic activity qualifies as contributing substantially to (1) climate change *mitigation* (Annex 1), or (2) climate change *adaptation* (Annex 2). They also give criteria for determining whether that economic activity causes no significant harm to any of the other environmental objectives. The economic activity is described briefly and the description is supplemented with NACE codes. Only a subset of economic activities are listed with criteria that would qualify them aligned. This is clear to see when looking at the activities listed under manufacturing or energy.

The Taxonomy Regulation and the two delegated acts are one single piece of legislation. Four more annexes with technical criteria for the other environmental objectives of the Taxonomy Regulation – sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems – will follow separately.

In a rather radical way, the Taxonomy Regulation describes the world as black and white: activities are either aligned or not aligned. There is nothing in between. Ultimately, companies, investors and banks have to report the percentage of aligned activities. For our purposes, it is important to note that there are no GHG disclosure requirements, and the taxonomy does not refer to GHG intensities for threshold values, either in absolute terms or regarding best practices, as such comparisons cannot currently be made.

Important change is often incremental, and sometimes less environmentally friendly options may be unavoidable. Quite often, it may be worthwhile to choose carefully between existing options. The taxonomy does not provide any guidance in such circumstances.

A second track of reporting obligations, associated with the *Non-Financial Reporting Directive (NFRD)***,** may in the long run be a better candidate for closing this gap. The NFRD, Directive 2014/95/EU of 22 October 2014,[37] concerns the disclosure of non-

[37] Here is a link to the NFRD, and to a press release on the reform.

financial and diversity information by large undertakings and groups. The Directive asks large companies for a rather encompassing statement on ESG issues, but does not go into any details in terms of what should be reported and according to what standards. Essentially, large companies and the head companies of large groups are supposed to report information on "environmental, social and employee matters, respect for human rights, anti-corruption and bribery matters, including: (a) a brief description of the undertaking's business model; (b) a description of the policies pursued by the undertaking in relation to those matters, including due diligence processes implemented; (c) the outcome of those policies."

The NFRD is considered rather ineffective, as companies are mostly free to choose what to report and the metrics and format that they use. A new piece of legislation means to change this. On 21 April 2021, the Commission adopted a proposal for a *Corporate Sustainability Reporting Directive (CSRD)*,[38] which would amend the existing reporting requirements of the NFRD. The proposal:

- extends the scope to all large companies and all companies listed on regulated markets (except listed micro-enterprises);
- requires the audit (assurance) of reported information;
- introduces more detailed reporting requirements, and a requirement to report according to mandatory EU sustainability reporting standards.

Importantly, it requires companies to digitally "tag" the reported information to make it machine readable.

As it is, however, the CSRD proposal is still an empty legislative shell. It specifies who is subject to reporting requirements and the reporting process, but not what to report. Much like the Taxonomy Regulation's delegated acts, the content of the reporting obligations will be defined separately. The contents are currently being prepared by the European Financial Reporting Advisory Group (EFRAG), an EU-funded non-profit organisation. A first draft of the reporting standards is expected by mid-2022. It will then be submitted for consultation. Given the scope of companies it covers, the audit requirements and the type of information to be disclosed, the CSRD is in an ideal position to incorporate GHG emissions reporting obligations.

[38] Here is a link to the CSRD proposal, and to a press release on the need to review the NFRD.