

A Model for Estimating Greenhouse Gas Emissions of Small and Medium Enterprises

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Abstract

This paper presents a comprehensive methodology for assessing greenhouse gas (GHG) emissions of small and medium-sized enterprises (SMEs), focusing on the integration of an environmentally extended multi-regional input-output (EEMRIO) model. Recognizing the significant contribution of SMEs to global emissions and their challenges in adopting standardized GHG accounting due to resource constraints, the study proposes a scalable and accessible tool tailored for an initial assessment of their environmental footprints. The model draws on EXIOBASE data, capturing both direct and indirect emissions across 163 industries in 44 countries. It estimates emissions by linking revenues and expenditures to country- and sector-specific CO₂ intensities, adjusted for inflation. Furthermore, through a case study on an exemplified Italian textile SME, the paper demonstrates the tool's application and produces a detailed estimate of combustion-based CO₂ emissions across Scopes 1, 2, and upstream 3 categories. This work offers SMEs a practical starting point for emissions measurement and reporting, supporting the requirement for enhanced transparency requested by financial institutions and policymakers, ultimately encouraging more robust sustainability practices.

Keywords: *Ghg emission; SMEs; Environmentally Extended Input-Output Models; EXIOBASE.*

1. Introduction

Climate change is among the most serious challenges of our time and stems, among the others, from the increasing concentration of greenhouse gases (GHGs) in the atmosphere. These emissions are primarily driven by human activities related to economic production and consumption and have material impacts on human welfare, disrupting food security, undermining public health, increasing vulnerability in housing and infrastructure, and accelerating environmental degradation. Thus, climate change cannot be understood solely as an environmental issue. It constitutes a complex and systemic challenge that affects political governance, economic development, and, overall, social equity. Addressing it requires coordinated and evidence-based policy responses that account for its wide-ranging and interdependent effects. As such, addressing climate change requires comprehensive, policy-based strategies grounded in empirical evidence. In order to formulate and implement such strategies, regulators must rely on robust data and well-defined indicators, aimed at monitoring and evaluating the effects of climate change and its causes.

In particular, greenhouse gases (GHGs) refer to a group of gases that concentrate in the Earth's atmosphere and absorb infrared radiation, not allowing heat to escape to outer space and generating what is known as the natural greenhouse effect. However, since the industrial revolution, the concentration of GHGs in the atmosphere, principally due to emissions stemming from human activities, has risen almost by 70% (Sakata et al., 2024) increasing the average temperature of the earth by more than one degree Celsius. The main GHGs induced by human activity are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and fluorinated gases (F-gases). At the moment, the global trend in greenhouse gas (GHG) emissions is not yet aligned with the achievement of carbon neutrality by 2050 (D'Arcangelo et al., 2022). However, after COVID-19 pandemic many governments have allocated significant funding recovery packages to green-transition policies – such as those that encourage investments in energy efficiency and renewable energy – and have increased taxation of emission-intensive goods and activities (Aulie et al., 2023).

Given the huge role of GHG emissions, it is gradually becoming an imperative that both large multinational enterprises and small- and medium-sized enterprises (SMEs) actively engage in their measurement and reporting, ultimately aiming at GHG emissions reduction (Hendrichs and Busch, 2012). Since 1998, it has become necessary to account for and report on greenhouse

gas (GHG) emissions, and the Greenhouse Gas Protocol (GHG Protocol) is a comprehensive and standardised global framework useful for these objectives. The GHG Protocol establishes the most widely adopted standards in the world for GHG emissions measurement and is a reference point for a wide array of organisations, including governments, businesses, and NGOs. The Protocol's objectives are to provide a credible and transparent approach for quantifying and reporting GHG reductions from GHG projects; to enhance the credibility of GHG project accounting through the application of common accounting concepts, procedures, and principles; and to provide a platform for harmonization among different project-based GHG initiatives and programs. Similarly, the International Finance Corporation (IFC) provides a broad institutional perspective in its "Technical Guidance for Financial Institutions – Assessment of Greenhouse Gases." This guidance offers a standardized framework for financial institutions to evaluate the GHG emissions associated with their investments and value chain. By emphasizing alignment with global standards such as the GHG Protocol, the IFC ensures consistency and comparability across industries and geographies. The document covers the assessment of Scope 1, 2, and 3 emissions, with detailed methodologies for tackling the often-complex task of accounting for indirect emissions. While primarily aimed at financial institutions, this guidance also addresses firms by incentivizing them to adopt transparent and rigorous GHG accounting practices. However, implementing these standards often requires capacity building within firms and their stakeholders, particularly for the more complex Scope 3 emissions.

Aligned with these regulatory efforts, various methods of accounting for carbon emissions have been examined in the literature, such as IPCC emission factors approaches (e.g. Shan, et al., 2016), LCA analysis (e.g. Liu, et al., 2023) and input-output models (e.g. Duchin, 1992; Wiedmann and Lenzen, 2007; Miller and Blair, 2009; Lenzen et al., 2012).

In such a scenario, small and medium-sized enterprises (SMEs) play a significant role, considering that 99% of European businesses are SMEs and they provide jobs to more than 85 million European citizens. Consequently, SMEs are the heart of entrepreneurship and are asked to substantially contribute to innovation and to the development of a sustainable and digital economy. Therefore, supporting the green transition of small and medium-sized enterprises (SMEs) is important to achieve global climate targets. However, while large corporations are often the focus of policies aimed at emissions reduction efforts, small and medium enterprises (SMEs) collectively contribute significantly to global emissions. However, due to limited

resources and expertise, SMEs often struggle to accurately measure and manage their emissions due to the lack of comprehensive data on their environmental performance, including carbon emissions, water usage, waste generation, and pollution levels. Furthermore, SMEs may not have the resources or expertise to track and report on these metrics accurately, encompassing a wide range of industries, sizes, and operational complexities. Each SME operates differently, with unique environmental risks and impacts associated with their activities. Therefore, there is a critical need for a tailored approach to help SMEs estimate and mitigate their GHG emissions effectively. For these reasons, the aim of this paper is to evaluate and quantify the environmental impact of SMEs through a GHG emission tool based on an Environmentally extended Multi Regional Input Output model (EEMRIO), particularly focusing on their operations and value chains. This process involves not only direct but also indirect environmental impacts related to suppliers and customers. Overall, the paper provides a useful tool to help SMEs to initially assess their environmental footprint. Furthermore, it may encourage banks to enhance transparency, accountability, and promote sustainability in their lending practices while supporting SMEs in their transition toward more environmentally responsible operations.

The remainder of the paper is organised as follows: Section 2 Literature review delves into the debate about carbon accounting and GHG emissions measurement. Section 3 Proposed Methodology describes the methodological design of the developed tool. Section 4 Practical Applications shows the main outcomes of the analysis on an exemplified case study. Section 5 concludes.

2. Literature Review

2.1 Institutional Background

Climate change has been increasingly recognized in recent years as a high-priority issue worldwide (Munasinghe, 2010; Princiotta and Loughlin, 2014; Martens et al., 2016) caused by industrial and human activities (IPCC, 2014; Saka, et al 2014). The Intergovernmental Panel on Climate Change (IPCC) defines climate change as *“a change in the state of the climate that can be identified... by changes in the mean and/or the variability of its properties and that persists for an extended period”* (IPCC, 2018). Climate change leads to changes in ecosystems, desertification, rise in sea level, flooding, and drought (Hisano et al., 2018; Ouhamdouch et al.,

2019). In 2015, the Paris Agreement, the first global agreement to reduce carbon emissions, was adopted at the 21st United Nations Climate Change Conference. The ultimate objective of the regulation was limiting the increase in the global temperature to below 2°C compared to pre-industrial levels by 2030¹. The European Union has set itself the goal of achieving carbon neutrality by 2050 and promoting sustainable development through measures such as the use of renewable energy sources, improving energy efficiency and ultimately promoting the development of more efficient and low-carbon technologies (Cervantes et al, 2023).

In November 2018, the European Commission presented a long-term strategic vision to reduce greenhouse gas (GHG) emissions, showing how Europe can lead the way to climate neutrality – an economy with net-zero GHG emissions. In other words, the strategy explores how this can be achieved by looking at all the key economic sectors, including energy, transport, industry and agriculture. A portfolio of options was explored to underline that it is possible to move to net-zero GHG emissions by 2050, based on existing or emerging technological solutions in key areas such as industrial policy, finance or research, while ensuring social fairness for a just transition. In such scenario, it is useful not to confuse carbon efficiency with energy efficiency.

In order to clarify corporate efforts to climate change mitigation, regulatory are increasingly mandating disclosure among firms. Overall, relevant disclosure rules are included in:

- The Sustainable Finance Disclosure Regulation (SFDR) entered into force since March 2021 and imposing disclosure obligations at both the entity and product level for financial market participants;
- The Taxonomy Regulation, providing a classification system for environmentally sustainable economic activities and directing capital flows toward green investments, aligning market practices with EU climate objectives;
- ECB Guide on Climate-Related and Environmental Risks, published in 2020 and outlining the European Central Bank's expectations for how banks should manage and disclose their climate-related and environmental risks as part of sound risk management;

¹ <https://unfccc.int/process-and-meetings/the-paris-agreement>

- EBA Implementing Technical Standards (ITS) on Pillar 3 ESG Risk Disclosure, adopted in 2022, to define the required disclosures of environmental, social, and governance (ESG) risks under Pillar 3 of the Capital Requirements Regulation;
- Corporate Sustainability Reporting Directive (CSRD), replacing the Non-Financial Reporting Directive (NFRD), and broadening the scope of mandatory sustainability reporting to include more companies and introduces more detailed reporting standards aligned with EU sustainability goals.
- EBA Guidelines on the Management of ESG Risks (Currently under development), to provide financial institutions with a comprehensive framework for integrating ESG risks into their governance, risk management, and business strategies;
- Green Bonds Regulation (Still under negotiation) to establish a voluntary EU Green Bond Standard, ensuring transparency and credibility in the green bond market by aligning it with the Taxonomy Regulation.

In particular, on 21st April 2021, the European Commission adopted a proposal for a Corporate Sustainability Reporting Directive (CSRD), entered into force in 2023. The CSRD applies to all large companies and all companies listed on regulated markets (except listed micro-companies). The rules also apply to listed SMEs, taking into account their specific characteristics and to non-European companies, generating a net turnover of €150 million in the EU and which have at least one subsidiary or branch in the EU. The CSRD envisages the adoption of a defined set of mandatory EU sustainability reporting standards, adopted by the European Commission as delegated acts, based on technical advice provided by the European Financial Reporting Advisory Group (EFRAG). Listed SMEs are allowed to report according to simplified standards, while non-listed SMEs adopt them voluntarily. Reporting will need to be certified by an accredited independent auditor or certifier (for non-EU companies, either a European auditor or one established in a third country). Sustainability information should be clearly identifiable through a dedicated section of the management report and a digitalization system will be required.

Credit institutions are in scope to the CSRD to the extent that they are large companies or companies listed on regulated markets. Banks face several challenges when it comes to disclosing the environmental impact of loans to small and medium enterprises (SMEs). These challenges stem from various factors, including the nature of SMEs, the complexity of environmental impact assessment, and the lack of standardized reporting frameworks.

In order to make non-financial disclosures on the classification of financial products and the related requirements consistent and comparable across EU jurisdictions and along the investment chain, the disclosure framework is increasingly based on the EU Taxonomy, when sustainable products or those with environmental or social characteristics. Established by the Taxonomy Regulation and subsequent Delegated Acts (some still pending) from the European Commission (EC), the EU Taxonomy provides a common classification system and uniform technical screening criteria to determine which economic activities make a substantial contribution to reaching EU environmental objectives, while at the same time causing no significant harm to the environment and respecting minimum safeguards.

Several significant international initiatives are shaping the global sustainability agenda and are expected to influence the development of the EU regulatory framework by promoting harmonization and best practices across markets:

- Network of Central Banks and Supervisors for Greening the Financial System (NGFS), launched in 2017 to support the integration of climate-related risks into financial supervision and decision-making;
- G20 Task Force on Nature-related Financial Disclosures (TNFD), building on the framework of the Task Force on Climate-related Financial Disclosures (TCFD), to develop an integrated risk management and disclosure system for nature-related risks;
- Financial Stability Board (FSB) Roadmap with a coordinated global roadmap to manage climate-related financial risks;
- International Sustainability Standards Board (ISSB), established by the IFRS Foundation in 2021, developing a comprehensive set of IFRS Sustainability Disclosure Standards aimed at creating a global baseline for corporate sustainability reporting;
- Net-Zero Alliances, including the Net-Zero Banking Alliance, the Net-Zero Insurance Alliance, and the Net-Zero Asset Owner Alliance.

2.2 Carbon accounting

Bebbington and Larrinaga-González (2008) identify three key implications of climate change for corporate accounting: (1) the financial accounting of emission allowances under emissions

trading schemes, (2) the reporting of climate-related risks to corporate performance, and (3) the need to address climate uncertainty through integrated, interdisciplinary approaches. Their work supports earlier calls for normative accounting research (Gray, 2002) and greater engagement between researchers and practitioners (Adams and Larrinaga-González, 2007), particularly in developing accounting practices that contribute to climate action. In a similar vein, Hopwood (2009) highlights the growing demand for environmental information as organizational interaction with ecological systems increases. He points to evolving accounting practices, such as environmental reporting, project appraisal, and cost–benefit analysis.

Building on these perspectives, carbon accounting, also referred to as greenhouse gas (GHG) accounting, has emerged as a vital tool for corporate climate governance. It functions across institutional and geographical levels and is essential for informed decision-making aimed at reducing emissions (Nartey, 2018). In practice, carbon accounting involves two core components: the systematic collection of emissions data and the processing of this information to evaluate the effectiveness of decarbonization strategies. Robust data collection is crucial for ensuring the reliability and utility of carbon accounting systems, which ultimately support meaningful progress toward emissions reduction goals (Farbstein et al., 2023).

Several methodologies for carbon accounting have been developed and examined in the literature. One of the most widely used is the IPCC emission factor approach, which estimates carbon emissions from specific activities using standardized emission factors (Shan et al., 2016). A more comprehensive alternative is Life Cycle Assessment (LCA), which captures emissions across the entire life cycle of a product or process (Liu et al., 2023). Finally, the input–output (IO) model offers a macro-level view by quantifying inter-sectoral emissions and their distribution across the economy (Huang et al., 2019). This approach is especially relevant for studying carbon flows embedded in trade between regions and countries (Mi et al., 2019; Yuan et al., 2022; Cabernard et al., 2022).

The seminal literature on carbon accounting is both diverse and interdisciplinary, reflecting the complexity of its application and relevance. Braun (2009) and Callon (2009) examine the sociological construction of carbon markets as socio-technical systems. From a policy perspective, Boston and Lempp (2011) explore the governance challenges of climate change, describing it as a “super wicked problem” due to its urgency, complexity, and institutional fragmentation (Lazarus, 2008). On the technical front, studies such as those by Johnston, Sefcik, and Soderstrom (2008) and Freedman and Stagliano (2008) investigate sulphur dioxide

emissions accounting. Other contributions focus on national and corporate practices—for example, Hogan et al. (2011) analyze corporate carbon reporting in Australia, while Knox-Hayes and Levy (2011) discuss carbon disclosure as a form of political governance. Lippert (2015) presents carbon accounting as a performative practice shaping organizational narratives.

More recently, the study of carbon emissions continues to gain traction with huge potential for meaningful change in economic activity and promote emissions reductions (Sheng et al., 2025). Mikes and Metzner (2023) examine how the effectiveness of corporate control systems is contingent upon a firm's orientation toward decarbonization. Their findings suggest that measurement, control, and disclosure of decarbonization performance and particularly regarding Scope 1, 2, and 3 emissions, are crucial for aligning environmental strategies with broader business operations, including mergers and acquisitions. The authors argue that carbon accounting is not merely a compliance tool but can also serve as a driver of strategic transformation through the adoption of green technologies and renewable resources. Zhang et al. (2017), in their study on China's embedded carbon emissions in international trade, highlight discrepancies in measurement techniques and reported figures across the literature. Yu et al. (2021) provide a comprehensive review of carbon leakage, identifying its primary causes, measurement approaches, and variations in outcomes across countries. Similarly, Tian et al. (2018) review the embodied environmental flows in global trade but focus more on research subjects than on methodological frameworks.

While earlier studies have demonstrated the informative value of carbon accounting in advancing corporate sustainability across economic, environmental, and social dimensions, it remains a contested and evolving field. Continued development is needed to enhance accounting tools and information systems that support effective decarbonization strategies.

2.3. Carbon Accounting for SMEs

Unlike large corporations, which may follow established sustainability reporting frameworks like the Global Reporting Initiative (GRI) or the Task Force on Climate-related Financial Disclosures (TCFD), SMEs often lack standardized reporting requirements for environmental performance. In particular, Moss et al. (2008) explore how small and medium enterprises (SMEs) can implement life cycle assessment (LCA) methods to evaluate their carbon

footprints. The study highlights the importance of using LCA to provide a comprehensive view of GHG emissions across the entire life cycle of products, from raw material extraction to end-of-life disposal. However, the study emphasizes that while LCA offers detailed and scientifically robust insights into emissions, its application in SMEs faces significant challenges due to resource limitations, lack of expertise, and the complexity of data collection. To address these barriers, simplified LCA methodologies tailored to the needs and capacities of SMEs can be employed, prioritizing key stages or processes with the highest emissions ("hotspots") to reduce the data and computational burden.

Eleftheriadis and Anagnostopoulou (2024) develop a tool tailored to SMEs for calculating their carbon footprint. This tool incorporates elements such as Scope 1 (direct emissions), Scope 2 (indirect emissions from energy use), and estimating Scope 3 (other indirect emissions) where data permits. While the tool is accessible and adaptable across industries, its simplifications may lead to trade-offs in precision, especially in complex supply chains or industries with highly variable emissions factors.

From a sector-specific standpoint, Alromaizan et al. (2023) develop a carbon accounting tool for SMEs in the agri-food sector, recognizing the unique challenges of this industry, such as seasonal fluctuations, reliance on agricultural inputs, and the significant contribution of methane and nitrous oxide. The tool is designed to identify emissions hotspots like fertilizer use and transportation while accommodating the variability inherent in agricultural processes. Focusing on the tourism sector in the UK, Berners-Lee et al. (2011) present an approach for estimating GHG footprint for small businesses using input-output (IO) data. Their study highlights the utility of IO data in estimating emissions by linking economic activity with environmental impacts across supply chains. This methodology is particularly beneficial for small firms that lack the resources for direct emissions measurement. By employing sectoral economic data, the authors demonstrate how upstream and downstream emissions can be estimated without extensive primary data collection. A potential limitation lies in the aggregation of IO tables, which may obscure sector-specific variations and lead to uncertainties in detailed emission estimates. The paper establishes a foundation for cost-effective carbon accounting, showing how IO models can fill data gaps while still offering meaningful insights into the carbon footprints of small businesses. Finally, by employing a global multi-regional input-output (MRIO) analysis, Schulte et al. (2024) provide evidence of the intrinsic uncertainties related to MRIO models, which are often used to trace emissions across international supply chains, identify error margins, and address data harmonization challenges.

This is particularly relevant for firms operating within globalized supply chains, where accurate emissions tracking depends on reconciling diverse data sources.

3. Proposed Methodology

To Input-output models were firstly theorized by Leontief (1941) and have ever since received wide attention and recognition in the world of economics (including a Nobel Prize for Professor Leontief in 1973). The framework is also called "inter-industry analysis" and focuses on modelling the interdependencies among industries in an economy. The basic idea is that, as an additional unit of a product is demanded, a certain combination of other (intermediate) products is required to produce that unit, for each of these intermediate products another combination of input is demanded and so on. The overall effect of these interdependencies is that a change in demand equal to, say, 1 unit of product A, causes a change in the overall production that is in general well above the market price of the additional unit demanded. This is called the Leontief multiplier and has a straightforward mathematical interpretation.

The input-output model provides a framework of analysis for interdependence amongst industries within an economic area. Since it is basically an accounting framework, it can be applied to the individual firm, provided that we identify the various components and the technological structure (in the Leontief sense) in each of their components. The economic activities of a company can be broken up into a number of separate, but interactive business units, or individual cost centers. The data needed are flows of products and services amongst these entities. When constructing an input-output model for a country or a region (macroeconomic level) it is possible in theory to record all the exchanges either in physical or in monetary terms. But since most sectors produce and sell more than one product or service, using physical units of measure poses a big challenge in aggregating the data. Input-output models are therefore mostly built in monetary units (prices) and the same can be said for firm-level (microeconomic level) applications.

An Environmentally Extended Input-Output Model (EEIO) integrates environmental data with economic input-output analysis to assess the environmental impacts associated with economic activities. The mathematical formulation builds upon the standard Leontief input-output model and adds environmental components. Several studies have attempted to integrate environmental considerations within the framework of IO matrices (e.g. Duchin, 1992; Miller

and Blair, 2009). Leontief (1970) develop a seminal attempt to consider the pollution repercussions of human economic activities considered under a traditional IO framework. Similarly, Wiedmann and Lenzen (2007) explore the environmental and social repercussions of international trade relationships, observing a spillover of negative impacts from developed to developing countries (e.g. US-China). More recently, Lenzen et al. (2012) propose an impressive environmentally extended multi-region input–output attempt to infer about the global responsibilities for emissions embodied in internationally traded products. Overall, EEIO represent a valuable source of useful information on the impacts associated with economic activities (Hertwich et al., 2009).

3.1 Model Development

Our model uses the multi-regional Environmentally Extended Supply-Use Table (MR-SUT) and the Input-Output Table (MR-IOT) from EXIOBASE². In particular, the environmentally extended multi-regional input-output table (EE MRIO) includes 200 products classified in 163 industries, expressed in millions of euros at current basic prices. It aggregates data from 44 countries, which include 28 European countries and 16 other major economies, along with five regions representing the rest of the world. More specifically we use EXIOBASE 3.9.5 version (Stadler et al., 2025). In the following steps, we outline the specific methodology used. First, we calculate the direct greenhouse gas (GHG) emissions triggered by a unit of financial output. Next, we analyze the final demand matrix to estimate the indirect emissions attributable to a company based on its corporate expenditures worldwide.

In what follows, we write matrices and vectors in capital letters while referring to individual matrix elements in lowercase.

Step 1: Definition of total output per sector.

We express the standard economic input-output model as:

$$x = Ax + y$$

² <https://www.exiobase.eu/index.php/about-exiobase>, accessed on: 05/05/2025

where: x is the vector of total output of all sectors ($n \times 1$); A is the technical coefficients matrix ($n \times n$), where each element a_{ij} represents the input from sector i required to produce one unit of output in sector j , and y is the vector of final demand ($n \times 1$).

Step 2: Determination of technical coefficients matrix.

We calculate the Leontief inverse (L), by rearranging the total output as follows:

$$x = (I - A)^{-1}y$$

where I is the identity matrix, and $(I - A)^{-1}$ represents the Leontief inverse, which captures the direct and indirect input requirements to meet a unit of final demand. In particular, the Leontief inverse is a matrix of sectoral output coefficients prompted by units of final demand. We express the final demand in basic prices.

Step 3: Inclusion of environmental factors in the IO setting.

To include environmental impacts (Miller and Blair, 1985), we introduce a vector of environmental coefficients that can be expressed as follows:

$$e = [e_1, e_2, \dots, e_n]^T$$

where each element e_i represents the environmental impact (e.g., emissions, resource use) per unit of output in sector i . At this stage, we simultaneously retrieve combustion originating from energy use (Stadler et al., 2018; Rasul et al., 2024) and non-combustion emissions (Stadler et al., 2018) from the environmental extension data. Specifically, we extract 418 environmental stressors combining all the different kinds of emissions attributable to each output sector per unit of final demand. In this sense, we can express the total environmental impact, denoted by E , as follows:

$$E = e^T x$$

Substituting x from the Leontief equation, we can rewrite the equation as:

$$E = e^T (I - A)^{-1} y$$

e is replaced by a matrix F ($m \times n$) containing environmental coefficients, where each row corresponds to an environmental indicator, and each column corresponds to a sector for each country. After, we can re-arrange the equation to express the total environmental impact vector E ($m \times 1$) for a single sector in a given country as per the following equation:

$$E = F(I - A)^{-1}y$$

where E represents the total environmental impacts for all indicators, while F is the environmental coefficients matrix.

Step 4: Vector of emissions for unit of financial output.

We first focus on CO₂ emissions derived from combustion activities. Thus, we define g as the vector of GHG emissions directly attributable to each sector and divide g by the vector of total output per sector x . As result we obtain a vector of coefficients of CO₂ intensity for each sector per unit of output G .

$$G_i = g_i/x_i.$$

Step 5: Matrix of emissions per unit of final demand.

We can express the matrix E of CO₂ emissions originating from each sector i per unit of final demand in each sector j as:

$$e_{ij} = l_{ij} \cdot g_i \quad i=1 \text{ to } 163 \text{ (industries)}; j=1 \text{ to } 163 \text{ (industries)}.$$

Step 6: Matrix of total emissions attributable to a company.

We now estimate the total direct and indirect CO₂ emissions attributable to each sector i originating from the final demand for each sector as:

$$E_{TOTALij} = y \cdot e_{ij} \quad i=1 \text{ to } 163 \text{ (industries)}; j=1 \text{ to } 163 \text{ (industries)}$$

where y is the vector of final demand ($i \times 1$). The same procedure can be generalized to all potential environmental stressors, ranging from non-combustion GHG emissions to various alternative environmental indicators included in the environmental extension data from Exiobase3.

Step 7: Inflation-related adjustments.

The basic approach for fully capturing the corporate environmental footprint is to consider corporate spending. In this context, total emissions per sector from the final demand of each sector serve as the benchmark for calculating the share of emissions attributable to a single company based on its spending. Since the values represented in the final demand coefficients reflect the current values of 2022, it is necessary to adjust the emission factor for the current level of spending at current prices. Therefore, we divide the emission factor of each sector ($E_{TOTALij}$) by the country-specific compounded inflation growth observed in 2023 and 2024 to account for potential inflation-related price increases, resulting in a decrease in emissions per unit of spending. Although this approach allows us to mitigate the flaw of IO tables that present outdated data by at least two years, the model cannot reflect the potential increase in industry efficiency in pollution emission prevention and treatment since the dataset was released.

Step 8: Identification of direct emission from the company.

The approach we describe allows us to estimate a company's indirect emissions based on its expenditures across the 163 industry sectors included in our environmentally extended input-output table. In this context, to estimate a company's direct emissions resulting from its operations, we multiply the company's net revenues by the emission factor calculated in Step 4 (the ratio of the vector of GHG emissions attributable to each sector to the vector of total output of each sector). However, we recognize that this approach does not permit isolating the specific processes that trigger most of the direct emissions, as is the case with life-cycle assessment (LCA) approaches.

Step 9: Identification of indirect emission from the company.

The model described so far can estimate the emissions attributable to a company's business operations, particularly focusing on its activities, expenditures, and the related impact of its supply chain, while excluding the indirect emissions attributable to the company's customers. Specifically, the model allows for the disaggregation of a company's entire carbon footprint by considering the individual contributions of the 163 industries included in the environmentally extended input-output table.

Overall, the standardized procedure across all industries and the ease of data collection are the main advantages of the model applied in the study, primarily requiring data from company bills and expenditure accounts. However, there are potential flaws related to the standardized structure of the model. Among others, the technical coefficients (the matrix of industrial output coefficients triggered by a unit of final demand) and the emissions factor per unit of financial output are considered homogeneous within sectors (Crawford, 2008; Berners-Lee et al., 2011).

3.2. Validation and benchmarking

One of the main challenges for SMEs is the validity and accuracy of their carbon footprint calculations. On the one hand, the model can easily estimate the potential impact of management decisions on corporate emissions concerning value chain, suppliers, and expenditure levels by sector. On the other hand, a crucial factor to consider in ensuring the model's effectiveness is the uncertainty in calculating both the technical coefficients and the direct estimates of emissions per unit of financial output produced.

In this regard, the first source of uncertainty arises from the standardized structure of the model, which implies homogeneity within sectors per unit of final demand. A second aspect relates to the accuracy of the baseline data itself. In this context, consider the potential effect of using casted values for the input-output tables extended to the environmental component. Additionally, another element of uncertainty involves the necessary inflation adjustment to account for an organization's level of expenditure, which fully considers the potential increase in basic prices and results in a corresponding decrease in emissions per unit of expenditure within the model.

For these reasons, it is urgent to emphasize, given the speed at which technological development affects civil society and all production processes by enhancing their efficiency, that the historical basis of the information in the input-output tables used does not permit us to evaluate and consider the evolution of technologies and production efficiency within each sector when estimating emissions by companies. To address this type of uncertainty regarding the accuracy of the data, some studies, such as that of Berners-Lee et al. (2011), have proposed a specific level of uncertainty in the initial data, estimated at approximately 10%. Specifically, the authors show how such uncertainty in the baseline information can result in a fluctuation

in the individual technical coefficients of the Leontief matrices ranging from zero to approximately 20%.

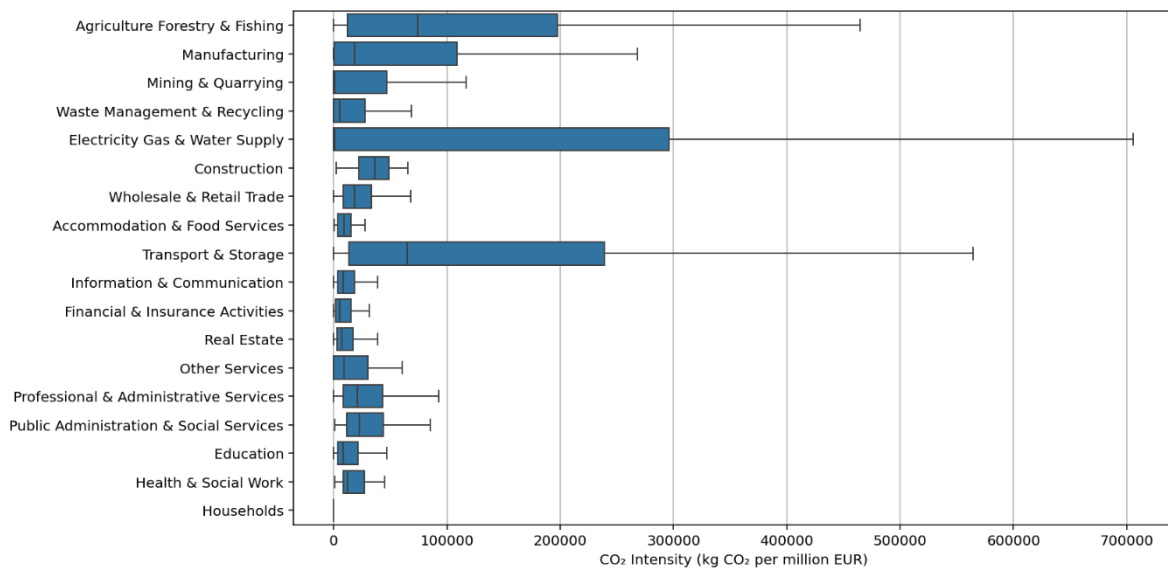
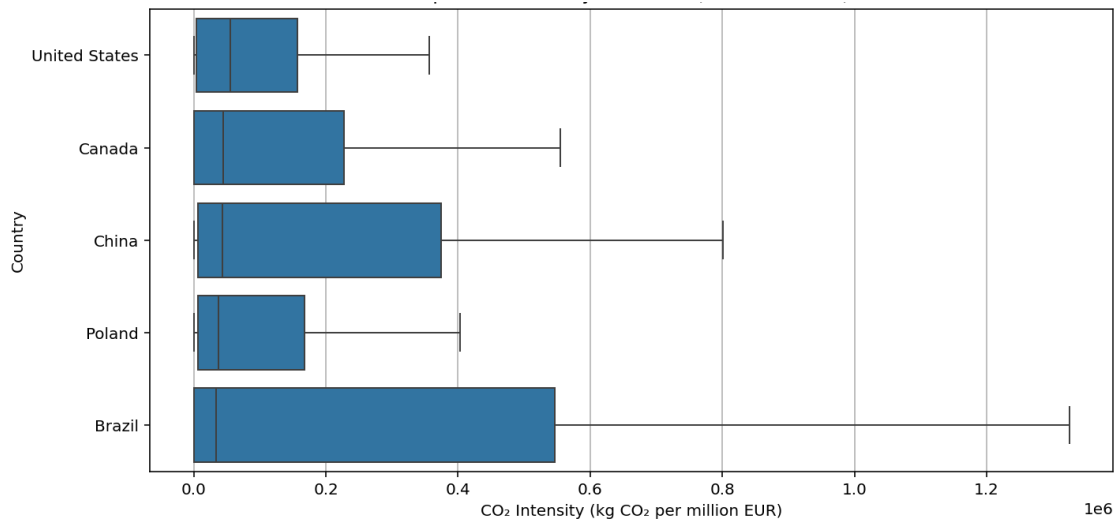


Figure 1 - Boxplot analysis of the median CO₂ intensity per industry

Authors' elaboration based on EXIOBASE data

The boxplot analysis of CO₂ intensity in Figure 1 shows the median emission intensity across sector buckets, built on NACE classifications of the 163 activities in EXIOBASE. The figure reveals an intriguing and significant inter-sectoral variability in their emissions per unit of economic output. As expected, sectors like agriculture, transport, and construction exhibit higher median intensities, and notable standard deviations, reflecting a potential energy and resource-intensive nature. Conversely, service-oriented sectors such as education, finance, and health display lower and more concentrated intensity distributions. Notably, in sectors such as "*Electricity, Gas & Water Supply*" and "*Waste Management & Recycling*" the figure shows extremely high upper ranges, suggesting the dominance of emission-intensive sub-sectors like coal-based electricity.



*Figure 2 - Boxplot analysis of the median CO₂ intensity for the top 5 emitters within our sample
Authors' elaboration based on EXIOBASE data*

Figure 2 illustrates the distribution of CO₂ intensity (kg CO₂ per million EUR of output) across the five most polluting countries, highlighting substantial inter-country variability in the carbon efficiency of economic activities. In detail, Brazil appears as the worst emitter within our sample, showing the highest median and upper-bound intensities, suggesting the presence of emission-intensive sectors within the country's economy. Furthermore, both China and Canada show wide variation in the distribution of their economic activities intensities, reflecting diverse sectoral profiles that include both high-emission industrial processes and relatively cleaner service or hydro-based energy sectors. In contrast, the United States and Poland display more concentrated distributions, indicative of more uniform emissions across their economic sectors. This heterogeneity reinforces the need for country-based estimation of combustion-based carbon emissions, as identical financial activities can yield substantially different carbon footprints depending on the national infrastructure of belonging.

4. Practical Application

We evaluate the applicability of the tool by testing the input-output modelling principles and estimating the combustion-related carbon dioxide (CO₂) equivalent emissions of an Italian SME, according to the European Commission definition, in the textile industry. The model leverages country- and sector-specific CO₂ intensities, expressed as kg CO₂ per million EUR,

derived through input-output methodology, to estimate combustion related emissions across Scopes 1, 2, and upstream 3 based on the enterprise's financial flows.

This approach prioritizes accessibility and adaptability, which are critical for small and medium-sized enterprises, SMEs, that often lack the data, resources, or technical capacity to conduct comprehensive environmental assessments or life cycle inventories. By relying on readily available disclosed financial data, specifically expenditures and revenues, the tool provides an efficient and replicable way to generate initial, yet meaningful, insights into an organization's operational emissions and environmental footprint. The interactive tool we design aims to estimate a company's CO₂ emissions based on its revenues and expenditures across different countries and economic sectors. The user initially indicates the countries where the company generate its revenues (or approximates it with the company's headquarters), choosing within the list of countries available for EXIOBASE data.

Then, the user may choose the specific sector(s) from a list grouped by NACE categories where the firm operates and provides the revenue distribution by each sector indicated. The tool allows the user to select a "Not Specified" category, which adopts the median intensity within the bucket as a value. This option allows approximating a company's footprint even without a granular distinction of expenses per sector. This amount indicated is multiplied by sector-specific CO₂ intensities (emissions per million EUR) to calculate revenue-based emissions, approximating direct emissions. Then, the user selects the countries and sectors where the company incurs its most relevant costs. The function similarly calculates cost-based emissions, which approximate indirect, and supply chain related upstream emissions, using the expenditure values and the relevant CO₂ intensities. This enables a combined estimate of emissions associated with both the firm income and spending activities, tailored to specific geographies and industries. The granularity of details available allows a more precise assessment of the company footprint.

In a practical application, we draw on an approximation of the financial data from an Italian textile sector firm as a representative case. First, 19 million EUR in revenues, reported in June 2024, are allocated to the Italian *"Manufacture of wearing apparel; dressing and dyeing of fur"* sector. For simplicity, and due to the absence of more disaggregated data, we attribute this revenue to operations held in Italy. Meanwhile, around 12 million EUR in reported expenditures. In detail, the costs are split in around 5,2 million euros evenly distributed between the *Electricity Gas & Water Supply* and the *Manufacturing* sector and around 7 million evenly

distributed for the *Transport & Storage, Professional & Administrative Services* and *Health & Social Work*, to reasonably reflect the functioning of an enterprise in the same industry. Given the absence of more detailed information on the distribution of costs, the expenses are assigned to the Not Specified category within each bucket, resulting in the median intensity of the overall bucket in the country. These inputs yield an estimated total of 547,611 kg CO₂, comprising 240,368 kg CO₂ from revenue-based emissions and 307,243 kg CO₂ from cost-based emissions. This breakdown not only demonstrates the internal consistency of the model but also its ability to distinguish between emissions tied to a company's value creation and those embedded within its supply chain and operational infrastructure. The results validate in this context the model's functional logic, testing its ability to produce nuanced estimates of GHG emissions from different sectors and geographies. However, it is crucial to emphasize that these values represent only a partial view of a firm's carbon footprint. They are grounded in assumptions informed by publicly reported financial figures, without access to granular data on revenue streams, production technologies, or supply chain composition. Additionally, the model excludes non-combustion GHG emissions, such as those from industrial processes, refrigerants, or land-use changes, which are vital components of a comprehensive Scope 3 inventory.

Type	Country	Sector	Amount (MEUR)	Overall Emissions (kg CO ₂)
Revenue	Italy	<i>Manufacturing - Manufacture of wearing apparel; dressing and dyeing of fur (NACE 18)</i>	19,000,000€	547,611 kg CO₂
Expenditure	Italy	<i>Electricity, Gas & Water Supply - Not specified category</i>	2,610,000€	
Expenditure	Italy	<i>Manufacturing - Not specified category</i>	2,610,000€	
Expenditure	Italy	<i>Transport & Storage - Not specified category</i>	2,350,000€	
Expenditure	Italy	<i>Health & Social Work - Not specified category</i>	2,350,000€	
Expenditure	Italy	<i>Professional & Administrative Services - Not specified category</i>	2,350,000€	

Table 1 - Summary of the inputs adopted in the example and estimated output

Thus, while the tool stands as a reliable and accessible entry point for GHG accounting, particularly useful in early-stage reporting or sustainability planning, it can benefit significantly from future refinement. In other words, while the model offers an accessible tool to gather first insights on a firm carbon footprint, users should avoid interpreting results as comprehensive

emission inventories without further contextual or activity-level data. Enhancements might include the integration of activity-based emissions factors, supplier-specific data, or hybrid methodologies incorporating process-based life cycle inventories. In its current configuration, the model presents a scalable, credible approach for organizations to gain actionable insight into their climate impacts using the data they already have and represents an important step toward broader environmental accountability.

5. Conclusions and Future Work

In this study, we aim to address the pressing issue of estimating the greenhouse gas (GHG) footprint of European small and medium-sized enterprises (SMEs). Overall, our work aims to contribute to the academic debate surrounding the environmental impact of SMEs within the broader regulatory and economic framework designed to reduce emissions and foster the transition to a low-carbon economy. Specifically, we provide practical support to SMEs for estimating their carbon footprint. In this context, we utilize a model based on the environmental extended input-output tables. After, we develop a tool that adapts to different levels of detail in the company's expenditure to estimate the impact of the value chain on a company's total emissions. However, it is important to note that the model can estimate upstream emissions within the value chain, but it does not account for the effects of final consumer behaviour on total emissions.

In this context, this work provides practical assistance to SMEs in estimating their impact, thereby offering a potential tool to evaluate the effects of potential management decisions on suppliers, production efficiency, and company expenditures, ultimately reducing corporate environmental impact. Additionally, this study can highlight potential implications for policymakers by enhancing the disclosure and the quantity of data related to the environmental impact of SMEs.

However, our study has limitations. First, potential uncertainty stems from the accuracy of the original data and the rigidity of the environmental extended input-output tables, which reflect historical data from at least two years ago. These tables do not support the evaluation of process efficiency resulting from technological evolution, providing a static and standardized overview

of the impacts on a sector's output based on the unit contribution of another sector to its final demand.

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