Advancing ESG reporting through life cycle assessment in semiconductor manufacturing: tools, frameworks, and opportunities

Advancing ESG Reporting through Life Cycle Assessment in Semiconductor Manufacturing: Tools, Frameworks, and Opportunities

C.P. Leo[1,*], Kok Hwa Yu[2], Mariatti Jaafar[3], Ngo Anh Dao Ho[4], Nagham Saeed[5]

[1] School of Chemical Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.
chcpleo@usm.my
[2] School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Seberang Perai Selatan, Penang, 14300, Malaysia
[3] School of Materials and Mineral Resources Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, 14300, Malaysia
[4] Faculty of Environment and Labour Safety, Ton Duc Thang University, 19 Nguyen Huu Tho Street, Tan Phong Ward, District 7, Ho Chi Minh City, Vietnam
[5] School of Computing and Engineering, University of West London, St Mary's Road, Ealing, London W5 5RF, United Kingdom

Abstract. The semiconductor industry plays a pivotal role in enabling modern technologies, yet its manufacturing processes are among the most resource- and energy-intensive in the electronics sector. As environmental, social, and governance (ESG) reporting becomes a strategic imperative, Life Cycle Assessment (LCA) has emerged as an important methodology for quantifying and communicating the environmental impacts of semiconductor products across their entire lifecycle. This review paper presents a comprehensive analysis of recent advancements in LCA methodologies and their integration into ESG strategies for semiconductor manufacturers. It examines literature ranging from early economic input-output models to advanced, AI-driven digital twin frameworks, as adopted by leading firms. The review also highlights key contributions from recent studies on carbon footprint modeling, gate-to-gate boundary approaches, and the role of nanomaterials in sustainable electronics. Despite progress, challenges remain, including inconsistent data availability, the complexity of multi-tier supply chains, and the lack of harmonized industry-wide LCA standards. Additionally, accurately assessing Scope 3 emissions and addressing upstream impacts pose persistent difficulties. Regulatory shifts, such as the EU Green Claims Directive and increased investor scrutiny, further drive the need for transparent and credible LCA-based ESG reporting. This paper concludes by identifying existing methodological gaps and proposing future research directions, including the development of semiconductor-specific product category rules (PCRs), standardized data platforms, and deeper supplier engagement.

Keywords: Life cycle assessment, ESG, Semiconductor

1 Sustainability Reporting in the Semiconductor Industry

Semiconductors are essential to modern technology, significantly contributing to advancements in diverse fields such as consumer electronics and high-performance computing. The intricate manufacturing processes involved in producing semiconductor devices carry a substantial environmental footprint, which should be revealed in Environmental, Social, and Governance (ESG) reports. Table 1 shows the scope of different standards and their applicability to the semiconductor industry while Fig. 1 shows the major element in GRI sustainability reporting.

Table 1. ESG reporting standards

Standard / Regulation	Scope	Applicability	Ref.
Global Reporting Initiative (GRI)	Broad sustainability disclosure (environmental, social, governance)	Encourages transparency in energy, emissions, and supply chain impacts	[1]
Sustainability Accounting Standards Board (SASB)	Industry-specific ESG metrics	Provides tailored metrics for hardware and semiconductor companies	[2]
Task Force on Climate-related Financial Disclosures (TCFD)	Climate-related financial risk and governance disclosure	Helps assess and report carbon risks in operations and value chain	[3]
Corporate Sustainability Reporting Directive (CSRD) (EU)	Mandatory ESG reporting for large companies operating in the EU	Requires EU-based fabs and suppliers to report in a standardized format	[4]
Carbon Disclosure Project (CDP)	Voluntary disclosure of carbon, water, and forest risks	Semiconductor firms report emissions and energy sourcing transparency	[5]
Greenhouse Gas Protocol (GHG Protocol)	Emissions accounting across Scope 1, 2, and 3	Enables tracking of fab emissions, purchased electricity, and suppliers	[6]
ISO 14001: Environmental Management Systems	Certification for environmental management practices	Promotes systematic control of environmental impacts in manufacturing	[7]
Responsible Business Alliance (RBA) Code of Conduct	Standards for labour, ethics, environment, and health/safety	Widely adopted in the electronics supply chain	[8]
Product Environmental Footprint (PEF) (EU)	Method for measuring the environmental performance of products	Supports LCA-based evaluation of semiconductor components	[9]

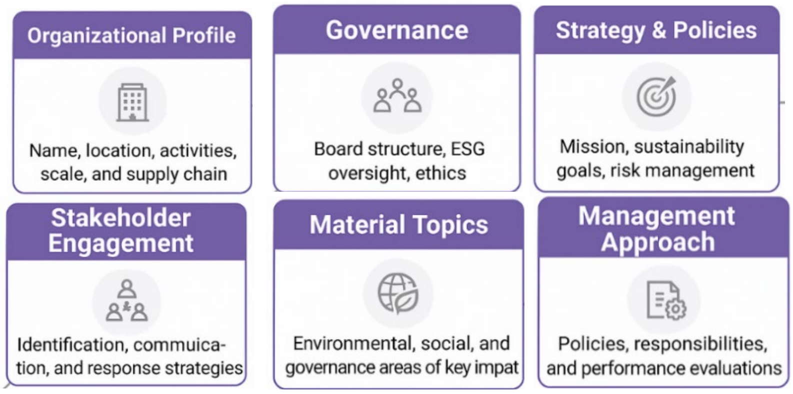

Fig. 1. Major elements of ESG report according to GRI standards [1].

Greenhouse gas (GHG) emissions in ESG reporting are categorized into three scopes under the GHG Protocol. Scope 1 covers direct emissions from sources owned or controlled by a company, while Scope 2 refers to indirect greenhouse gas emissions resulting from the production of electricity, steam, or cooling that is acquired and used by an organization. Scope 3 accounts for all other indirect emissions across the value chain, both upstream and downstream, encompassing processes such as material sourcing, supplier operations, product usage, and final disposal. A comparative analysis of the 2023–2024 ESG reports from Intel, TSMC, Samsung Semiconductor, GlobalFoundries, and Micron reveals a strong and maturing industry-wide commitment to sustainability, transparency, and corporate accountability. Intel leads with its robust RISE 2030 strategy, embedding ESG targets into business operations and pursuing an aggressive net-zero target by 2040, backed by renewable energy investments and advanced water reuse initiatives [10]. TSMC stands out for its rigorous supplier ESG audits, ISO-certified environmental and safety systems, and a growing focus on social responsibility through dedicated human rights reporting and internal ESG innovation programs [11]. Samsung Semiconductor, through the broader corporate lens of Samsung Electronics, aligns its ESG disclosures with GRI and TCFD, while steadily enhancing its energy efficiency, responsible materials sourcing, and emissions monitoring [12]. GlobalFoundries focuses on environmental health and safety, diversity, and equity, with recognized ESG ratings and a clear roadmap to achieve net-zero emissions by 2050 [13]. Meanwhile, Micron has made major strides in emissions reduction, aiming for 100% renewable energy in key regions by 2025, and is actively participating in circular economy initiatives such as the Semiconductor Climate Consortium [14]. Together, these players demonstrate the semiconductor industry's transition from compliance-driven ESG to proactive leadership in climate action, ethical supply chain management, workforce well-being, and product sustainability. Their evolving strategies reflect not only regulatory expectations but also investor pressure and global market demand for greener, more transparent semiconductor technologies.

2 Life Cycle Assessment for the Semiconductor Industry

LCA plays an important role in strengthening ESG reporting by offering a standardized, data-driven approach to quantifying the environmental impacts of products and processes across their entire lifecycle. In the semiconductor industry, LCA enables companies to identify carbon hotspots, optimize resource use, and address Scope 1, 2, and particularly Scope 3 emissions with greater accuracy. Incorporating LCA into ESG strategies supports compliance with emerging regulations such as the EU Green Claims Directive and enhances transparency for investors and stakeholders. LCA serves as both a compliance tool and a strategic enabler for long-term environmental and economic sustainability. LCA is a structured approach used to assess environmental impacts across a product's entire lifespan, covering stages from resource extraction to manufacturing, usage, and final disposal, as defined and structured under ISO 14040 and ISO 14044 standards [15, 16]. According to ISO 14040:2006, LCA consists of four major phases:

(i) Goal and Scope Definition – Defining the study's objective, the system boundaries, and the required level of detail.

(ii) Life Cycle Inventory (LCI) – Gathering comprehensive data on resource inputs (such as materials and energy) and outputs (including emissions and waste) across each stage of the product's life cycle.

(iii) Life Cycle Impact Assessment (LCIA) – Evaluating potential environmental impacts (e.g., climate change, acidification, water use) using the inventory data.

(iv) Interpretation – Concluding and making recommendations based on the findings, while ensuring consistency with the stated goal and scope.

In the semiconductor industry, LCA following ISO standards enables companies to quantify environmental hotspots, improve eco-design, and align with ESG reporting by providing robust and comparable environmental data across complex global supply chains.

The evolution of LCA in the semiconductor sector began with foundational studies that quantified environmental burdens in electronics manufacturing. Deng et al. [17] introduced a hybrid economic-input-output LCA for laptops, identifying energy-intensive processes in integrated circuit (IC) packaging and emphasizing uncertainties in data and boundary definitions. Asadi et al. [18] further extended this approach with a comprehensive LCA framework tailored to the semiconductor value chain, accounting for upstream material extraction, fabrication, and end-of-life stages. Huang et al. [19] developed a parametric carbon footprint model for wafer fabrication processes, identifying technology nodes, mask layers, and metal layers as key predictors of emissions. Belkhir and Elmeligi [20] presented a broader perspective by estimating the global carbon footprint of the ICT industry. Kang et al. [21] analyzed the life cycle of smartphones in China using site-specific data. Their study demonstrated that component manufacturing, especially semiconductor devices, dominated environmental impacts. That same year, Sivaraman et al. [22] introduced a modular carbon footprint modeling tool for semiconductor facilities, enabling real-time emissions tracking and sensitivity analysis. This regression-based model supports gate-to-gate assessment and design scenario evaluation, making it valuable for internal process optimization and ESG reporting. Liu et al. [23] examined the environmental implications of nanomaterials in electronics, emphasizing their dual role in improving device performance and reducing energy and material footprints. Their review also suggested that nanomaterials could be integral to sustainable next-generation semiconductor manufacturing. More recently, Microsoft's LCA Methodology v2.1 [24] represents a major shift toward digitalized, AI-driven LCA practices. By integrating full material declarations, supplier-specific data, and IMEC's inventory, the methodology enables precise, part-level impact assessments across cradle-to-grave boundaries. This allows for effective hotspot identification and low-carbon design strategies. To address inconsistencies in LCA application across the electronics industry, Schischke et al. [25] and Proske et al. [26]contributed to the development of a Product Category Rule (PCR) tailored for electronics. Their work critiques limitations in ISO 14040/44 and EN 50693, and supports harmonized data collection and reporting methods across manufacturers and suppliers. Complementing this, Liu et al. [27] empirically validated lifecycle emissions for smartphones and data servers, reaffirming the dominant impact of semiconductor fabrication and the need for better Scope 3 data integration.

Together, these studies illustrate a clear progression from conceptual modeling and empirical data collection to advanced, digitized LCA practices that integrate regulatory alignment, supply chain collaboration, and sustainability innovation in the semiconductor industry. In conclusion, the integration of LCAinto ESG reporting within the semiconductor industry is essential for driving sustainable transformation. While leading companies have begun incorporating LCA to address Scope 1–3 emissions, significant challenges remain, particularly in standardizing data collection across complex global supply chains and in quantifying Scope 3 impacts. The current gaps in sector-specific LCA databases, limited transparency in upstream processes, and inconsistent reporting frameworks hinder comprehensive assessments.

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