

Hardware Is an AI Ethics Problem: Expert Visions for a Sustainable and Equitable Semiconductor Industry

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Abstract

As the foundation of contemporary AI systems, the semiconductor industry is increasingly shaped by critical social, environmental, and geopolitical challenges. Nonetheless, prior research has often examined these issues in isolation and within disciplinary silos, leaving a gap in understanding them through an integrative socio-technical, cross-disciplinary lens. To address this gap, we conducted a participatory futuring workshop with experts from academia, industry, and policy. The results of our analysis show that the aforementioned challenges are highly interdependent, and participants envisioned interconnected socio-technical pathways linking present frictions to normative goals. Drawing from their perspectives, we highlight three central tensions: the sovereignty–sustainability tension, where national protectionism undermines ecological survival; supply chain opacity, which obscures accountability for labor and environmental harms; and a growing knowledge divide that risks excluding smaller economies from shaping the AI future. Participants envisioned futures centered on interdependence and inclusive access, proposing measures such as a standardized emissions labeling system to translate technical data into public accountability. They also suggested frameworks for strategic interdependence to balance local resilience with global cooperation, and epistemic redistribution initiatives to lower barriers of entry and democratize access to hardware infrastructure. We argue that considerations of AI ethics must extend beyond models and data to encompass the hardware infrastructures on which they depend, and that embedding stakeholder reflection is critical for anticipatory governance in the physical infrastructure of AI.

Processing Units (GPUs) used to train frontier Large Language Models (LLMs) (Lee et al. 2025; Narayanan et al. 2021). However, their global supply chains are characterized by technical, environmental, social, and geopolitical risks. Massive resource demands (energy, water, minerals), persistent chemicals and gas emissions, opaque supplier networks, and geographically uneven labor protections create vulnerabilities. Critical accounts have traced these dependencies as constitutive of AI itself, situating computation within a planetary economy of extraction and labor (Crawford 2023). Simultaneously, accelerating demand for compute and intensified geopolitical competition amplify pressures on capacity, resilience, governance, and global access.

While prior work has examined discrete, sector-specific challenges across different segments of the supply chain—including materials (Williams, Ayres, and Heller 2002; Tsai, Chen, and Hsien 2002; Xu and Schoonen 2000; Yoon et al. 2020), fabrication (Mullen and Morris 2021; Yoon et al. 2020; Ruberti 2023), logistics (Sachan and Datta 2005; Sandberg et al. 2022; Anaba, Kess-Momoh, and Ayo-deji 2024; Le and Fan 2024), impacts (Kuo, Kuo, and Chen 2022; Ruberti 2023; Ghulam and Abushammala 2023), and policy (Wu, Ding, and Cheng 2024; Vickerman 2024)—existing debates remain fragmented across disciplinary and stakeholder boundaries and largely treat these challenges in isolation. Recent work has begun to situate the hardware layer within the AI lifecycle, mapping AI supply chains as interconnected spheres spanning extraction to e-waste (Muldoon, Valdivia, and Badger 2026), yet this interconnection is drawn between lifecycle stages rather than between the challenges themselves. Still missing is an account that treats semiconductor supply chain challenges as interconnected and often competing socio-technical tensions, and that grounds such an analysis in the perspectives of multiple stakeholder groups. Furthermore, despite growing interest and research in AI ethics, AI governance and responsible AI, material infrastructures, such as semiconductor supply chains, remain underexamined in relation to questions of fairness, sustainability, and global access in AI systems.

To address this gap, we provide an interdisciplinary, expert-driven, stakeholder-based synthesis that captures these interconnections and translates them into actionable

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1 Introduction

Semiconductors are crucial components of electronic devices. They have gained increasing strategic value during the current “AI Race” (Cave and Óh Éigeartaigh 2018; Hwang 2018), because they are a key foundation of the Graphics

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measures for achieving coherent future trajectories for the sector. We conducted a two-day, in-person, collaborative multi-stakeholder workshop bringing together experts from academia, industry, and policy. Using a guided participatory approach, participants engaged in supply chain mapping and risk assessment (Harland, Brenchley, and Walker 2003; Ho et al. 2015), STEEPLE-based futures scenario analysis (Aguilar 1967; Moesgen et al. 2023; Epp et al. 2022; Hohendanner et al. 2024), and collaborative recommendation co-design (Earl, Carden, and Smutylo 2001). Drawing on futuring methodologies (Epp et al. 2022; Hohendanner et al. 2023, 2025b) and principles from reflective design (Hohendanner et al. 2025a; Sengers et al. 2005), the workshop enabled participants to surface systemic challenges across supply chain stages, assess their likelihood and impact, and articulate ideal future scenarios alongside concrete measures for a more inclusive and resilient semiconductor industry. Our study addresses the following research questions:

- **RQ1:** From expert participants' perspectives, what are the salient challenges and risks across the semiconductor supply chain, and what solutions do they propose?
- **RQ2:** What does an ideal future for the semiconductor industry look like, technologically, politically, environmentally, and socially, and what measures are necessary to achieve that?

This paper contributes a qualitative, stakeholder-grounded account of how experts across academia, industry, and policy understand the challenges, future aspirations, and governance tensions shaping the contemporary semiconductor industry. We synthesize participants' perspectives on systemic challenges, envisioned futures, and proposed measures, and articulate how these are connected into socio-technical pathways linking present conditions to normative goals.

This paper makes the following contributions:

1. **From isolated challenges to interconnected socio-technical tensions.** Prior work has examined semiconductor challenges (environmental, labor, geopolitical) in disciplinary isolation. We move beyond this fragmented treatment to show that these challenges are structurally interdependent: national sovereignty goals undermine sustainability, supply chain opacity enables labor and environmental impunity, and capital barriers reproduce global knowledge inequality. We make these interconnections explicit through three socio-technical tension pathways: the *sovereignty–sustainability tension*, where the pursuit of national sovereignty undermines ecological survival; *supply chain opacity*, which shields labor and environmental harms from accountability; and a *knowledge divide*, where capital barriers and export controls structurally exclude smaller economies from shaping the AI future.
2. **A cross-disciplinary, multi-stakeholder synthesis.** Existing debates on semiconductor ethics, sustainability, and geopolitics are largely siloed across policy, industry, and academic communities that rarely come in contact with each other. This paper initiates a cross-disciplinary dialogue by grounding its analysis in the perspectives of

experts from academia, industry, and policy simultaneously, offering an integrated account of systemic risk that cuts across disciplinary and sectoral boundaries.

3. **A framework for structural intervention.** We synthesize participant outputs into three domains of socio-technical intervention, *Radical Visibility*, *Strategic Interdependence*, and *Epistemic Redistribution*, moving beyond voluntary CSR measures to propose enforceable mechanisms for accountability (e.g., mandatory CO₂ labeling) and equity (e.g., open-source hardware funding).
4. **Normative pathways for anticipatory governance.** We articulate expert-driven future trajectories that contrast the risks of a “Rebound Effect” (where AI efficiency gains are swallowed by consumption) against a vision of “Sustainable Cooperation.” We detail the specific governance, technological, and social shifts required to bridge the gap between current frictions and these ideal futures.
5. **Semiconductor governance as a first-order concern of AI ethics.** We highlight the semiconductor supply chain as a critical yet often overlooked layer of AI ethics, showing that questions of fairness, sustainability, and global access in AI systems are already being determined at the level of chip fabrication, supply chain opacity, and export controls, long before a model is trained or deployed. By connecting algorithmic concerns to material infrastructures, we offer actionable insights for stakeholders, from governments to civil society, and call on the AI ethics communities to extend their lens upstream, treating hardware governance not as background infrastructure but as a foundational site of ethical inquiry.

Together, these contributions show how participatory methods can transform fragmented debates about semiconductors, competitiveness, and geopolitical risk into coherent pathways of accountable, anticipatory governance that link present-day vulnerabilities to ideal futures and actionable pathways.

2 Related Work

Semiconductors are fundamental materials that are used to build electronic components, including chips (Turley 2003). In the advancement of technology, chips are used in various applications, including automotive (Ahmad 2020) and health industries (Guida et al. 2019; Jovanov and Milenkovic 2011; Azghadi et al. 2020), portable devices such as smartphones (Kuo, Kuo, and Chen 2022), virtual reality headsets (Zhang 2024; Mii 2022), and numerous products powered by AI (Batra et al. 2019; Sipola et al. 2022). As these technologies evolve, so do the ethical, environmental, and social concerns surrounding their production. In this section, we review three core areas of scholarship relevant to our work: environmental sustainability, ethical labor considerations, and the role of participatory approaches in socio-technical governance.

2.1 Sustainability Considerations

While the semiconductor industry is driving significant technological advancements, it has substantial environmental effects during the different phases of its life cycle. A growing

body of research is examining the environmental sustainability of computing hardware (Yin and Yang 2025; Pirson et al. 2023; Elgamal et al. 2025).

Starting with the extraction and supply of raw materials and ending with the life of the device in which the semiconductor is used, the semiconductor industry processes result in diverse types of waste, involving a considerable amount of hazardous residues (Shen, Tran, and Minh Ly 2018; Ruberti 2023; Kuo, Kuo, and Chen 2022). Following rapid technological development, the replacement of semiconductor manufacturing equipment further increases e-waste challenges (Sun and Rose 2015). Surprisingly, research has found that foundries generating the highest revenues per wafer, a thin slice of semiconductor material on which integrated circuits are fabricated (Turley 2003), such as TSMC and SMIC, have the highest relative waste production (Ruberti 2023). A significant portion of e-waste generated in North America and Europe is exported annually to countries in Asia, South America, and Africa, largely driven by the lower cost of recycling and opportunities for illegal dumping, often disguised as charitable donations (Ghulam and Abushammala 2023). The improper handling of e-waste leads to significant consequences, including the emission of various toxic fumes into the ecosystem (Mullen and Morris 2021) and the leaching of lead and other substances into soil and groundwater, negatively impacting air, water, soil, and human health (Ghulam and Abushammala 2023; Pasricha and Wolf 2024).

Semiconductor production is a complex resource-intensive process where a substantial amount of energy, water, raw materials, gases and chemicals are used (Goswami 2023; Mullen and Morris 2021; Kuo, Kuo, and Chen 2022; Zhang et al. 2024; Ruberti 2023). The finite nature of most of these raw materials make them scarce and extremely valuable (Goswami 2023). Various chemicals used in semiconductor production pose a threat to Earth's ecosystems, as many of these substances are highly persistent, contributing to global warming (Mullen and Morris 2021). Additionally, the production of a single square meter of wafer requires thousands of tons of (ultrapure) water, which is also essential for wafer cleaning processes (Ruberti 2023). Wafers with finer patterning require even greater amounts of water (Ruberti 2023) as well as chemicals and materials for their production (Mullen and Morris 2021). Energy consumption has significantly escalated in the semiconductor industry (Mullen and Morris 2021), being primarily used to power production equipment (Ruberti 2023), maintain critical cleanroom conditions (Mullen and Morris 2021), and support the transportation of raw materials, waste, and products (Iacopi and McIntosh 2019).

The massive amounts of energy required to manufacture chips also produce carbon (Pasricha and Wolf 2024; Gupta et al. 2021) and greenhouse gas emissions, with energy consumption from nonrenewable sources adding a double burden to the overall environmental impact (Ruberti 2023; Zhang et al. 2024). This impact is considerable for telecommunication devices, which generate higher CO₂ emissions due to their increased number of mask layers required for complex circuit designs (Kuo, Kuo, and Chen 2022).

2.2 Ethical Considerations

The semiconductor industry, often perceived only as a high-tech sector, is deeply entangled with labor rights issues that originate in the raw material extraction phase of its supply chain. Critical minerals such as tantalum, tin, tungsten, collectively known as “conflict minerals”, are essential for semiconductor fabrication (Pasricha and Wolf 2024; Goswami 2023). Yet, their extraction is frequently associated with forced and child labor, particularly in regions such as the Democratic Republic of Congo (DRC), its neighbors (Pasricha and Wolf 2024) and other regions with inadequate regulatory oversight, where labor and human rights concerns remain significant (Ukonu 2025; Kuo, Kuo, and Chen 2022). In these mining regions, workers often face low wages, prolonged exposure to hazardous materials, and lack of proper ventilation and other safety measures (Ukonu 2025). These challenging labor conditions – including widespread exposure to hazardous chemicals and hazardous waste – are not only troubling from a labor rights perspective but also pose serious health risks to workers and surrounding populations (Yoon et al. 2020; Mullen and Morris 2021). A study conducted in 2020 on chemical use and associated health concerns in the semiconductor manufacturing industry showed that, on average, only 29% of all chemical constituents used in surveyed semiconductor workplaces had Occupational Exposure Limits, indicating that most chemicals used lack defined exposure guidelines (Kuo, Kuo, and Chen 2022). Many of these chemical products, including acids and constituents used in different semiconductor manufacturing processes have been shown to have a causal link to diverse occupational diseases (Yoon et al. 2020; Mullen and Morris 2021). The most frequently used toxic substances in semiconductor manufacturing are carcinogens, followed by reproductive toxins and mutagens (Yoon et al. 2020). This increases the risk of several types of cancer (e.g., non-Hodgkin's lymphoma, leukemia, brain tumors, lung, laryngeal and breast cancer), systemic poisoning, and reproductive abnormalities (including congenital malformation, reduced fertility and spontaneous abortions among women working directly in fabrication areas) (Yoon et al. 2020; Mullen and Morris 2021).

These concerns expand to later semiconductor phases. As mentioned above, improper disposal and recycling of semiconductor-related e-waste releases harmful substances like mercury and cadmium which pose serious health threats, such as respiratory issues, asthma, eye irritation and increases the risk of oral health problems such as periodontitis in children in contact with e-waste regions (Ghulam and Abushammala 2023). Despite these risks, it has been shown that many chemicals in use lack formal hazard assessments, in terms of reactivity, safety and health (Kuo, Kuo, and Chen 2022). Furthermore, a semiconductor life cycle impact assessment (Widheden and Ringström 2007) has shown that damage to human health, measured in disability-adjusted life years lost in the human population, outweighs impacts on ecosystems or resource depletion (Kuo, Kuo, and Chen 2022). A major barrier to protecting workers in the semiconductor industry against harm from chemical substances stems from the widespread use of trade se-

cret ingredients (Yoon et al. 2020). These ingredients refer to undisclosed chemicals, materials, or proprietary formulations used during chip fabrication, which are kept confidential for competitive or intellectual property reasons (Mullen and Morris 2021). A study, conducted in 2020, revealed that 33% of all chemical products used in surveyed semiconductor workplaces contained at least one trade secret ingredient (Yoon et al. 2020). This lack of transparency combined with limited access to hazard information makes it difficult to assess and manage hazardous chemicals, occupational risks, exposure analysis and the implementation of safety protocols (Kuo, Kuo, and Chen 2022; Yoon et al. 2020).

Beyond workplace safety and health concerns, transparency issues also hinder environmental accountability and corporate social responsibility. Methods such as life cycle assessment (LCA), which evaluates a product's environmental impact throughout its life cycle, relies heavily on input and output data, such as raw material and energy requirement, and outputs such as solid wastes, water pollutants, and other emissions (Widheden and Ringström 2007). Corporate Social Responsibility (CSR) reports, used to communicate an organization's social and sustainability performance, ideally include disclosure on their production practices, emissions, energy consumption, water withdrawal, and wastewater discharge (Ruberti 2023). However, in the semiconductor industry access to this data is often complex, limited, confidential, and inconsistent (Kuo, Kuo, and Chen 2022; Ruberti 2023; Bui 2024). Several researchers argue that transparency is crucial for understanding the complex materials, components, and the impacts of resources beyond energy, such as water and minerals, as well as emissions and manufacturing processes involved in semiconductor production, especially given the global dispersion of the different steps of the supply chain (Bui 2024; Pasricha and Wolf 2024; Ghulam and Abushammala 2023). Further, placing a strong emphasis on transparency also enables collaboration among various stakeholders within the supply chain (Bui 2024).

Some large IT companies, such as Apple, Amazon, Meta, Microsoft, and Google, publicly disclose their carbon emissions (Pasricha and Wolf 2024; Gupta et al. 2021; Google 2026; Apple Inc. 2025). Such disclosures are largely voluntary and self-scoped, with firms determining their own boundaries and accounting conventions. They have accordingly been criticized for understating true impact (Klaaßen and Stoll 2021; Crownhart 2025).

2.3 Research Gap and the Importance of Participatory Work

Participatory research (Kuhn and Muller 1993; Bødker and Kyng 2018) is increasingly recognized as crucial across several technological domains (Zytka et al. 2022; Delgado et al. 2023). Participatory approaches have shown strong potential for identifying and integrating diverse stakeholder values while distributing decision-making power more equitably (Bødker and Kyng 2018). However, participatory inquiry into the ethical and governance dimensions of semiconductor infrastructures, as well as the topic itself, remain largely absent from venues such as FAccT, CHI, CSCW, and AIES, despite semiconductors forming the physical infras-

tructure underlying contemporary AI systems. This represents a significant gap, as AI ethics research often focuses primarily on downstream algorithmic systems while overlooking the upstream material infrastructures, labor conditions, environmental externalities, and geopolitical dependencies that make AI possible.

Building on this foundation, we organized a two-day, in-person participatory workshop that convened experts from academia, industry, and policy. Together, participants identified key challenges and risks in the semiconductor supply chain, co-developed actionable recommendations, envisioned ideal future scenarios, and proposed concrete measures to address systemic vulnerabilities.

3 Methodology

3.1 Workshop Contextualization and Structure

Recognizing the importance of participatory approaches (Barreau et al. 2013), and with the primary aim of exploring experts' perspectives on the challenges and risks, recommendations, future visions for the semiconductor industry, and measures to reach idealistic futures, we conducted a two-day, in-person, multi-stakeholder workshop in a European country in early 2025. We incorporated participatory methods in collaborative structured activities enabling stakeholder co-development.

The study is guided by two central goals: (1) characterizing the current status quo of the semiconductor industry, and (2) envisioning its ideal future, both from the perspectives of industry, academia, and policy, with respect to ethical, social, political, and sustainability considerations. These goals are operationalized through two sub-questions for each of the two research questions: what challenges and risks experts perceive (Q1.1), what solutions they propose (Q1.2), what an ideal future looks like (Q2.1), and what measures are necessary to reach it (Q2.2). See details in Appendix A.3.

Each workshop day (5h) was divided into two parts. First, participants delivered short presentations related to their ongoing work and professional expertise (2h), which provided shared context but were not part of the structured analysis. Second, as shown in Figure 1, we guided participants through six stages, three activities per day in approximately 2 hours facilitated, group-based activities. At the beginning of each 2 hour session, we provided participants with a brief overview of the activities and objectives for the day. The activities were designed to, first, surface challenges and risks in the semiconductor industry (Q1.1), second, develop actionable recommendations to address the challenges and risks (Q1.2), third, co-develop futures (including the ideal futures: Q2.1) and, fourth, identify actionable measures to reach the ideal futures (Q2.2).

These activities were implemented using printed worksheets. The activity design was informed by prior work on participatory risk analysis (Ullstein et al. 2024) and participatory futuring (Hohendanner et al. 2025b), and further drew on the STEEPLE framework, used to structure futures reflection across different dimensions (Epp et al. 2022; Moesgen et al. 2023; Hohendanner et al. 2024) (see Appendix A.5). The design further adapted stages from Outcome Map-

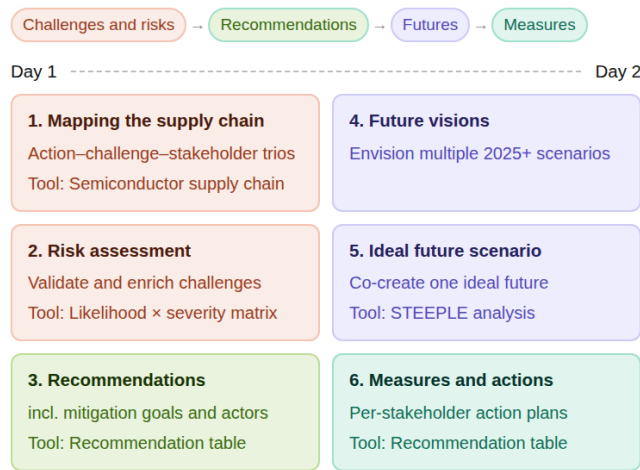


Figure 1: Overview of the activities, their workflow and the two-day participatory workshop design (see Appendix Figure 3 for details).

ping, a participatory planning approach that links goals to responsible actors and strategies (Earl, Carden, and Smutylo 2001) (see Appendix A.6). Finally, the design drew on principles of reflective design, which emphasizes embedding critical reflection into both action and decision-making processes (Sengers et al. 2005) (see Appendix A.4).

Participants were separated into predefined groups to ensure balanced representation across backgrounds and areas of expertise. Due to participants' scheduling constraints, the group composition varied across the two workshop days: on Day 1, participants were divided into three interdisciplinary groups ($N_1=5$, $N_2=4$, $N_3=4$), while on Day 2 they were divided into two ($N_1=6$, $N_2=5$). Some participants attended both sessions and others only one, meaning the samples across days were partially overlapping rather than identical. To maintain continuity, Day 2 activities took the Day 1 outputs as their starting point, and we opened Day 2 by briefing participants on the preceding day's results.

Each participant group was supported by two members of the organizational team: one acting as facilitator, ensuring that the structure and goals of the activity were clearly understood and followed, while the second acting as observer, tasked with documenting key points, participant contributions, and group dynamics by taking field notes to support later qualitative analysis.

3.2 Description of Workshop Activities

In the following, we detail each of the six activities depicted in Figure 1 (see Appendix A.8 for further details).

First activity: Mapping the Semiconductor Supply Chain to challenges. In the first activity (see Appendix Figure 4), participants mapped actions, challenges, and stakeholders across two to three pre-selected stages of the semiconductor supply chain (Ning, Tziantzioulis, and Wentzlaff 2023; Saha and Guin 2024; Xu et al. 2019), collaboratively developing "trios" of action-challenge-stakeholders.

Second Activity: Risk assessment-Probabilities and Impact. Building on established methodologies used in participatory work (Hohendanner et al. 2025b; Harland, Brechley, and Walker 2003; Ho et al. 2015), the second activity deepened challenge exploration through a structured risk assessment, where participants collaboratively populated a Likelihood vs. Severity Matrix across three levels of likelihood and impact.

Third Activity: Recommendations Addressing the Challenges and Risks. Building on the identified challenges and risks, participants jointly formulated actionable recommendations by specifying desired outcomes, responsible actors, and concrete actions (see Appendix Figure 5). The recommendation table design draws on reflective design (Sengers et al. 2005), Outcome Mapping (Earl, Carden, and Smutylo 2001), and participatory design principles (Hohendanner et al. 2025b; Friedman et al. 2013; Dombrowski, Harmon, and Fox 2016; Bødker and Kyng 2018; Sauppé and Mutlu 2014), prompting participants to articulate both what should change and who holds responsibility to act.

Fourth Activity: Future Visions. Connecting to futuring methodologies within HCI (Epp et al. 2022; Hohendanner et al. 2025b), this activity invited participants to collaboratively envision future scenarios for the semiconductor industry in 2030 and beyond (see Appendix Figure 12), voting on the most relevant trajectories.

Fifth Activity: Ideal Future Scenarios. Building on these envisioned futures, participants were invited to co-create and analyze ideal future scenarios through a simplified STEEPLE framework (Aguilar 1967; Moesgen et al. 2023; Epp et al. 2022) across technological, political, environmental, and social dimensions (see Appendix Figure 6). This scenario-building process works not merely as a visionary tool, but as a reflective and participatory method that makes normative futures actionable and discussable within a transdisciplinary group (Dunne and Raby 2024).

Sixth Activity: Measures and Actions to Achieve the Ideal Future Scenarios. In the final activity, participants identified stakeholder-specific measures for governments, industry, academia, NGOs, society, and other actors to realize the envisioned ideal futures. Drawing on Outcome Mapping (Earl, Carden, and Smutylo 2001), stakeholders are conceptualized as agents of change, emphasizing their active roles as researchers, policymakers, engineers, and civil society actors in enacting the futures they co-designed (Sengers et al. 2005).

3.3 Participants Selection

The workshop brought together 18 experts (see Appendix A.1 for the definition of expert) from academia ($N=5$), industry ($N=9$), and policy sectors ($N=4$), reflecting a range of professional perspectives and domain expertise across the semiconductor, sustainability and ethical ecosystem. To ensure a balanced and diverse representation across sectors, we adopted a hybrid recruitment approach, combining stratified purposive sampling (Palinkas et al. 2015) and targeted recruitment (Fung 2006). This balance was sectoral rather than demographic: participants were predominantly based in Germany and the wider European region, and only a limited

number of women participated. The perspectives reported here are therefore situated ones. For more details on sample demographics, selection and recruitment, see Appendix A.2.

In accordance with institutional guidelines, this study did not require formal ethics approval. We nevertheless adhered to established ethical standards. Participation was voluntary, and participants were informed about the scientific nature, objectives, structure, and expected outcomes of the workshop, as well as their right to withdraw at any time. All collected data were anonymized and handled in compliance with GDPR, and participants provided informed consent for the use of their data for scientific purposes.

To ensure participant well-being, each group was supported by a facilitator, and an additional member of the research team was responsible for monitoring participant comfort. A structured time protocol ensured sufficient breaks throughout the sessions.

3.4 Data Analysis

The qualitative data comprising participant-filled worksheets and facilitator observation notes were analyzed by four researchers. We applied Initial/Open Coding (Saldaña 2021) individually, then jointly consolidated the resulting codes into a final scheme (see Appendix Tables 4 and 5), consulting observer notes for additional context where needed. Across both phases, some contributions were coded to more than one domain. We treated these multi-coded items as indications of where challenge domains overlap, and represented this overlap structure rather than collapsing connections. From it, we identified three recurring patterns in which challenges in one domain generated frictions in another, and report these as the socio-technical tensions in Sections 4.2–4.4. The three intervention domains in Section 4.5 were derived correspondingly, by grouping the eleven recommendation categories according to which tension they address. The nine challenge domains and eleven recommendation categories are thus participant-derived; the tensions and intervention domains are our synthesis of them. For a full account of the coding procedure, intercoder discussion process, and category development, see Appendix B.

4 Results

4.1 Socio-technical challenges in the Semiconductor Industry

The participatory futuring process yielded a detailed map of the semiconductor supply chain’s systemic vulnerabilities and potential remedies. In total, participants’ contributions were coded into 9 interconnected challenge domains, ranging from *environmental constraints* to *industrial espionage* and *human rights* violations (see Figure 2). Their proposed interventions were grouped into 11 recommendation categories, including *transparency mechanisms*, *supplier redundancy*, *funding structures*, and *governance frameworks*. See Appendix C for a comprehensive descriptive catalog of these discrete outputs, including specific measures for stakeholders (e.g., governments, NGOs, industry) and detailed breakdowns of the identified challenges.

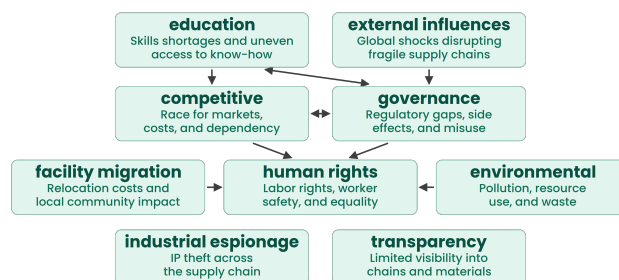


Figure 2: Interconnected systemic challenges in the semiconductor industry, coded from workshop participants’ contributions. The diagram illustrates 9 categories: environmental, facility migration, transparency, industrial espionage, education, competitive, governance, human rights, and external influences.

However, presenting these findings as isolated lists obscures the structural tensions inherent in the supply chain. Our analysis reveals that a challenge in one domain (e.g., geopolitical competition) can give rise to frictions in others (e.g., environmental degradation). Consequently, rather than cataloging individual data points, we synthesize the workshop outcomes into three interconnected socio-technical pathways (summarized in Table 1). Below, we structure the results by first detailing the *current systemic friction* identified by participants (**Q1.1**), followed by the *normative goal* or ideal future they envisioned (**Q2.1**), and finally, the *socio-technical bridge*, the concrete measures and recommendations (**Q1.2 and Q2.2**), required to traverse from the status quo to the target future. All text in quotation marks is participants’ written wording, reproduced verbatim.

4.2 The Sovereignty-Sustainability Tension: Geopolitical Decoupling vs. Environmental Goals

A central tension described by experts was between the semiconductor industry’s geopolitical positioning, competitive dynamics, and environmental obligations. Participants described the current status quo as an innovation and competitive advantage race characterized by export controls and national interests (e.g., Chips Acts), where regions invest in domestic production capacity to reduce geopolitical dependency. While these strategies aim to secure sovereignty and technological advantage, we identified a critical socio-technical tension: efforts to achieve national sovereignty systematically undermine global sustainability goals.

Participants identified a “Facility migration challenge”: Moving production for geopolitical reasons incurs high costs and local community impacts. By duplicating supply chains in pursuit of autonomy, regions multiply the industry’s already substantial resource footprint, including water and energy usage and eternal chemical (PFAS) emissions.

Furthermore, participants warned that the duplication of foundries for sovereignty can lead to a fragmentation of the global market. This fragmentation, they argued, can cause the industry to lose scale and directly contributes to less spe-

cialization, as regions are forced to replicate generic infrastructure rather than optimizing globally. This dynamic may foster weaponization and blocking of semiconductor technology and further reinforces “exclusionary effects of regulation [restricting access] of people to good technologies”. We read this as indicating that without intervention, regulatory tools intended for safety risk are repurposed as geopolitical instruments, in a system where environmental pollution and waste disposal are collateral damage in an escalating trade conflict.

To dismantle this tension and find a balance between local resilience and global scale, participants argued that resilience and sustainability in the industry requires interdependence, instead of pure self-sufficiency or dependency. Participants explicitly called for institutional cooperation through peace agreements, memoranda of collaboration and partnerships between different regions (e.g., university collaborations between Taiwan and Germany). To sustain this cooperation, participants assigned critical oversight roles to non-state actors: NGOs would take on the role of mediators regarding conflicts and provide recommendations in form of guidance documents and standards, acting as neutral arbiters in a polarized landscape. Simultaneously, academia would assess governments, ensuring that policy decisions remain accountable to empirical realities. Governance recommendations focused on a *One Voice strategy* for Europe, allowing the region to enforce deep, stable regulatory frameworks that prioritize shared sustainability goals through collective bargaining power. This envisions a balanced global market where regions specialize and trade under shared ethical frameworks, avoiding a new cold war, recognizing that green AI is impossible if the hardware layer relies on redundant, extraction-heavy supply chains.

4.3 Opacity, Transparency and Accountability in the Supply Chain

Opacity in the semiconductor supply chain is often treated as a necessity for security or IP protection. We read participants’ accounts as indicating that this opacity also functions as a shield for impunity. Participants described the industry as “monopolistic by design”, where the lack of traceability allows resource consumption, forever chemicals, other emissions and health hazards faced by workers to remain hidden deep in the supply network. This converges with legal-political analyses of AI’s global value chains, which show that lead firms actively compel the confidentiality and silence of suppliers through trade secrecy provisions and non-disclosure agreements (Terzis 2023), making opacity a legally constructed condition rather than an incidental property of complex supply networks.

This opacity creates a crisis of accountability: while downstream tech companies often claim “Net Zero” targets, the reality is that they have rather limited visibility into upstream origin of the materials, material sourcing, labor conditions, and environmental impact and emissions.

In response, participants envisioned an ideal future where “green buying decisions” become the standard, driven by a new public consciousness regarding the ecological cost of compute. To realize this accountability, participants pro-

posed a concrete socio-technical measure. The design of *The “CO₂/Emissions Semaphore”*: A standardized traffic-light labeling system (Green-Red, A-E) for semiconductor and electronics that informs buyers of a device’s production footprint, similar to the European Nutri-Score in food. This has the potential to translate technical emissions data into a socio-technical tool for public accountability.

This technical fix is paired with a governance requirement: establishing “more transparency of emissions of electronics devices” incentivizing adoption beyond the chip foundry to the end-device producers. This measure aims to transform *Transparency* from a corporate buzzword into a quantifiable and enforceable metric.

4.4 The Knowledge Divide and Global Inequality

The workshop surfaced deep anxieties about the weaponization of access to knowledge. Participants noted that current competitive challenges are not just about market share, but about structural exclusion. High capital expenditures (CAPEX) and export restrictions effectively lock the Global South and smaller nations out of the AI ecosystem, fueling an innovational and educational knowledge gap that reinforces power imbalances and the “monopoly by design”. Simultaneously, labor risks are displaced to regions with competitors emerging in other areas that may have weaker labor protections, creating a race to the bottom.

This exclusion raises important questions about equity and participation in the AI ecosystem: if certain regions cannot access or manufacture chips, they are structurally prevented from shaping the AI future, reduced to consumers of black-boxed technologies imported from the Global North. We link this to inequality and opportunity for nations, and argue that the current AI Race is reproducing colonial dynamics of resource extraction and technological dependency (Adams 2024; Mohamed, Png, and Isaac 2020).

The ideal future envisioned by participants is one of inclusive competitiveness, where governments take action to ensure (unlimited) access to technology.

The proposed pathway to this future relies on knowledge redistribution. Recommendations included setting up specific funding calls between regions to bring experts and the know-how and broader talent pools. Crucially, this includes capacity building measures where academia, NGOs and Governmental institutions act as stakeholders to educate individuals in the domain while raising awareness about the issue, lower barriers of entry and the implementation of regulations to ensure knowledge share. On the labor front, the optimization of labor laws across borders was seen as essential safeguarding human rights.

4.5 Transformative Interventions: Reconfiguring the Supply Chain

To bridge the gap between the current systemic frictions and the envisioned ideal futures, participants co-developed a set of measures functioning as socio-technical interventions. These recommendations go beyond technical optimization; they represent a reconfiguration of how the semiconductor supply chain is governed, perceived, and distributed. We

Present Frictions (Challenges)	Normative Goals (Ideal Future State)	Socio-technical Pathway (Recommendations)
The Sovereignty-Sustainability Tension: The race for competitive advantage and sovereignty via export controls creates a facility migration challenge and geopolitical dependency. The resulting fragmentation of the global market causes the industry to lose scale, results in less specialization, multiplies the footprint of water consumption and eternal chemicals (PFAS), and further reinforces exclusionary effects.	Sustainable Cooperation: A balanced global market that avoids a “new cold war”. Trade is conducted under shared sustainability goals rather than weaponized regulation.	Strategic Interdependence: • Cooperation: Establish Peace agreements and Memorandum of collaboration (e.g., EU-Taiwan). • Oversight: NGOs act as mediators regarding conflicts and academia should assess governments. • Governance: A “One Voice strategy” for Europe to enforce shared standards.
Opacity, Transparency and Accountability: The supply chain is monopolistic by design, acting as a shield where resource consumption, emissions, and health hazards remain hidden. Limited visibility prevents accountability regarding traceability origin of materials.	Conscious Consumption: A future where green buying decisions are the standard. Transparency transforms from a buzzword into a quantifiable metric.	Radical Transparency: • The CO₂ Semaphore: Implement standardized ecological scores in “Semaphores” (Green-Red, A-E labeling) for devices. • Governance: Enforce transparency of emissions beyond the foundry to end-device producers incentivizing adoption of the semaphore.
The Knowledge Divide and Global Inequality: “High CAPEX” and export restrictions fuel an innovational and educational knowledge gap and uneven access to knowledge, reinforcing power imbalance and potentially resulting in weaponization of access and structural exclusion. Labor risks are displaced to regions with competitors emerging that have weaker labor rights.	Inclusive Competitiveness: A future where governments ensure “(unlimited) access to technology”, treating innovation access as a public good.	Knowledge Redistribution: • Access: Funding to bring experts, the know-how, and <i>capacity building measures</i>: lower barriers of entry, implement regulations to ensure knowledge share, optimize labor laws across borders.

Table 1: From Systemic Challenges to Ideal Futures: A Socio-technical Pathway.

synthesize these measures into three intervention domains: *Radical Visibility*, *Strategic Interdependence*, and *Epistemic Redistribution*.

Intervention 1: From Voluntary Disclosure to Radical Visibility. The first domain of intervention targets the opacity that currently shields the industry from accountability. Participants argued that the current paradigm of voluntary Corporate Social Responsibility (CSR) is insufficient for the scale of environmental and ethical risks involved. Instead, they proposed a shift toward *Radical Visibility*, mechanisms that force externalities into the open.

Central to this is the above-mentioned proposal for a *CO₂ Semaphore*, a standardized, traffic-light rating system (Green–Red) displayed on end-user devices . From a socio-technical standpoint, this acts as a *boundary object* that translates complex, hidden supply chain data into a publicly actionable signal. By making the scale of CO₂ consumption visible, this measure is intended to shift the cognitive burden of environmental impact from the abstract (corporate reports) to the concrete (consumer choice).

This visibility extends upstream to the manufacturing floor. Participants recommended that industry players must create transparency regarding emissions and, crucially, implement material and pollution containment measures. This is not just to have a technical filter, but also a governance structure that defines a target for reduction, thereby transforming vague sustainability pledges into quantifiable accountability metrics. By linking these metrics to government funding, which many of the industrial actors rely on, the state can enforce transparency as a condition of market par-

ticipation and growth, rather than a corporate benevolence.

Intervention 2: From Autarky to Strategic Interdependence. The second intervention challenges the geopolitical trend toward isolationism and technological sovereignty. Participants recognized that supplier redundancy and second sourcing are necessary for resilience, while total decoupling from other countries and actors is ecologically and economically disastrous. The proposed alternative is *Strategic Interdependence*, a governance model that prioritizes stability and cooperation over dominance.

This is operationalized through the recommendation for Peace agreements and memorandum of collaboration between key semiconductor nations (e.g., EU, Taiwan, South Korea). Rather than viewing interdependence as a weakness, participants framed it as a mechanism to find a balance between local resilience and global scale. For the European context, this requires a One voice-strategy , unifying fragmented national interests into a cohesive bloc capable of enforcing deep and stable regulatory frameworks.

Crucially, this interdependence is underpinned by an anticartel practice enforcement. This measure acknowledges that a sustainable supply chain cannot exist under monopolistic conditions. By preventing the concentration of power, both corporate and geopolitical, these governance measures aim to create stability in frameworks that can generate trust, allowing innovation to proceed without being weaponized by external influences .

Intervention 3: Epistemic Redistribution and Infrastructural Equity. The final intervention addresses the knowledge divide by treating semiconductor expertise not

as a proprietary asset, but as a public good that requires active redistribution. Participants stated that the exclusion of the Global South and smaller economies from the AI revolution is rooted in a lack of access to the physical means of computation.

To counter this, the workshop yielded strong recommendations for Epistemic Redistribution. This involves promoting open sourcing models to break the monopoly on chip design, paired with funding calls and robust partnerships specifically aimed at transferring know-how from leading regions (like Taiwan) to emerging ecosystems.

However, knowledge transfer is ineffective without the human infrastructure to support it. Participants emphasized lowering barriers of entry for skilled workers and defining clear HR Goals to retain talent. This is a socio-technical recognition that supply chain resilience relies as much on community integration and optimizing labor laws as it does on raw materials. By prioritizing capacity building and educating individuals in the domain, these measures aim to democratize the semiconductor hierarchy, ensuring that the benefits of the AI era, and the capacity to shape it, are not hoarded by a few hegemonic actors.

5 Discussion

Our findings illustrate that the challenges and risks of the semiconductor industry, including environmental degradation, opaque supply chains, labor exploitation, and geopolitical dependencies, cannot be understood in isolation. Access to advanced chips is directly tied to national power, competitiveness, and even to democratic resilience and growth. What is at stake is not only the ability to innovate but also who controls the conditions of innovation and why, who bears the costs, and who benefits from the transition to digital and AI-driven economies.

In policy debates, semiconductors are increasingly framed as critical infrastructure (Lin, Dombrowski, and Bardzell 2025; Ning and Wentzlaff 2025). The EU Chips Act (European Parliament and Council 2023b), the U.S. CHIPS and Science Act (U.S. Congress 2022) and China's large-scale subsidies aim to secure technological sovereignty. Nonetheless, these initiatives often focus on competitiveness while neglecting transparency, labor standards, and environmental impacts. We argue that, without embedding ethics and sustainability into such frameworks, efforts to reduce risks in supply chains will only lead to reproducing the very vulnerabilities they seek to mitigate: simply relocating carbon footprint, environmental waste, or precarious labor conditions from one region to another. Similarly, export controls (Bureau of Industry and Security, U.S. Department of Commerce 2023; Ministry of Commerce (MOFCOM) and Ministry of Science and Technology (MOST), PRC 2023; Brockmann 2022) designed to limit innovation in other regions risk fragmenting global markets, reinforcing exclusionary dynamics, and reinforcing an arms race that neglects the socio-technical effects of the industry.

Focusing on the environmental impact, the sector's energy and water footprint remains largely absent from global sustainability frameworks such as the Paris Agreement (United

Nations Framework Convention on Climate Change (UNFCCC) 2015). Without binding commitments on emissions, recycling, and hazardous materials, the sector risks becoming a blind spot in global climate negotiations. Binding instruments, however, require a point of attachment. Building on our participants' proposal for a CO₂ Semaphore, we suggest attaching such a requirement at market entry, similar to the EU Battery Regulation and the Carbon Border Adjustment Mechanism do (European Parliament and Council 2023a): the operator placing a device on a market carries the obligation and passes it upstream contractually. Enforcement would thus not require jurisdiction over the entire chain, but it would require data. Although a lot has been discussed on the impact of training and deploying AI systems on the environment (Patterson et al. 2022; Lacoste et al. 2019; Patterson et al. 2021; Samsi et al. 2023), little has been investigated on how semiconductor supply chains contribute to this footprint. Closing this gap is therefore not only a research task but a precondition for making the sector's footprint governable at all.

Similarly, questions of inclusivity remain underexplored. The unequal distribution of talent, education, and research infrastructure needed in the semiconductor industry has as a consequence a global divide between compute- and chips-rich and poor countries (Lehdonvirta, Wú, and Hawkins 2024). Unless programs for facilitating knowledge transfer, open curricula, and international training are prioritized, efforts to strengthen sovereignty in specific countries will always increase structural inequalities globally. This has direct implications for equity and participation in the AI era: societies excluded from semiconductor access are de facto locked out of meaningful participation in shaping AI futures. This exclusion extends to the research communities that study these systems. Scientific venues are typically sited where an established research community already exists, a reasonable criterion in isolation, but circular in effect, since regions without such a community are also those where research is least visible as a field one might enter. In regions that receive technologies without participating in their production, hosting research venues could be a way to make this work visible locally and introduce younger students to it as a possible trajectory.

AI ethics is often addressed at the software layer, for example through analyses of model behavior or data practices. We argue that its concerns begin earlier. Opacity in AI systems does not only exist at the model; it is already present in the manufacturing of the hardware they run on. Our participants described the hardware layer as already structured in ways that exclude regions, through the weaponization of standards, export controls, and access regimes.

Taken together, these findings underscore the importance of embedding stakeholder reflection into the governance of the physical infrastructure underlying AI systems. As semiconductor supply chains shape the material conditions of AI development long before data collection or model deployment, governance interventions that occur only at the software or application layer arrive too late. Participatory approaches that reveal how different actors perceive risks, responsibilities, and trade-offs enable forms of anticipa-

tory governance that can address environmental, social, and geopolitical impacts upstream, before they are locked into infrastructural decisions. In this sense, stakeholder reflection is not merely a deliberative add-on, but a necessary condition for governing AI as a socio-technical system whose ethical implications are materially instantiated in hardware and supply chains.

Building on the need for anticipatory governance of AI's physical infrastructure, we make three normative claims. First, *resilience requires transparency*: full traceability of environmental and labor practices are necessary to reduce fragility in the supply chain while safe-guarding the environment. Second, *ethics and sustainability are inseparable from competitiveness*: environmental stewardship, labor protections, and inclusivity must be treated as conditions of long-term innovation, not as secondary concerns. Generating solid foundations for innovation will be beneficial in the long run, even if they seem costly in the short. Third, *global cooperation must be balanced with local empowerment*: multilateral frameworks should set standards for transparency, sustainability, and labor, while regions maintain sufficient autonomy to avoid coercive dependencies. As computing and AI becomes the new digital infrastructure, access to its own infrastructure should be considered a social good that is available to all.

The semiconductor industry needs to be resilient in the face of external shocks, ethical in its treatment of people and environments, and inclusive in distributing the benefits, especially during the current AI era. Building this future requires coordination across governments, industry, academia, NGOs, and civil society. Nonetheless, interconnected socio-technical pathways linking present conditions, normative goals, and actionable interventions discussed in this study provide a concrete starting point for moving from understanding to action.

6 Limitations and Future Work

Our workshop methodology enabled rich, interdisciplinary insights, yet several limitations must be acknowledged. Participation was not fully diverse in terms of gender and geography, with most contributors based in Europe. Generated within a two-day format, the outcomes remain strategic rather than operational, specifying what should change and who should act, but not the institutional detail through which measures would work. Future work should explore ways to translate high-level recommendations into operational frameworks, foster longer-term engagement and seek broader representation, including replication with industry workers upstream in the supply chain, policy actors, researchers, and communities living near production and extraction sites. Future work should also weigh the proposed measures against their costs. Finally, future work should explore the concrete design and evaluation of the proposed "CO₂/Emissions Semaphore" (see details in Appendix D).

7 Conclusion

This paper presented a participatory futuring workshop that brought together stakeholders from academia, industry, and

policy to critically reflect on the ethical, environmental, and geopolitical challenges of the semiconductor industry. Through a series of six structured activities, participants collaboratively identified nine interconnected challenge areas, co-developed eleven categories of actionable recommendations, articulated future visions and ideal scenarios, and proposed stakeholder-specific measures to realize them. Our findings further synthesize these into three interconnected socio-technical pathways linking present conditions, normative goals, and actionable interventions: the sovereignty–sustainability tension, supply chain opacity and accountability, and the knowledge divide and global inequality.

Current debates tend to treat semiconductors as a matter of industrial policy, environmental impact, or geopolitical competitiveness, almost always considering them within separate disciplinary silos. Our findings emphasize the importance of inclusive, multi-stakeholder dialogue in shaping the governance structures of this deeply infrastructural-technological domain. Participants stressed the urgency of addressing transparency gaps, knowledge asymmetries, and the unequal distribution of both the benefits and burdens of semiconductor production across the globe.

Beyond documenting these challenges, this paper makes a broader claim about what AI ethics needs to pay attention to. AI ethics has largely confined its attention to the software layer: model behavior, dataset practices, and algorithmic outputs. Yet, we argue that semiconductors and the hardware layer are not only the physical foundation of AI systems; they are also a foundational layer of AI ethics. The ethical implications of AI systems are not only instantiated in the training data selected or the outputs deployed; they are already being shaped at the level of which regions can fabricate chips, which workers bear the health costs of production, which chemicals are released in whose backyards, and which nations are structurally locked out of the hardware ecosystem. Governing AI responsibly, therefore, also requires governing its hardware layer responsibly, and that necessitates exactly the kind of anticipatory, multi-stakeholder reflection this study demonstrates.

We argue that engaging diverse expert perspectives in structured, speculative, and reflective formats enables the surfacing of nuanced risks, but also catalyzes the co-production of future-oriented responses. This work further highlights the value of participatory futuring as a research and design method for surfacing and shaping responsible trajectories in critical socio-technical systems and calls on the HCI, AI ethics, and responsible computing communities to treat the hardware layer not as background infrastructure, but as a first-order site of ethical inquiry.

Generative AI Usage Statement

Generative AI tools were used to assist language editing, rephrasing, and improving the readability of the manuscript. The tools did not contribute to data collection, analysis, or decision-making.

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