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Making microelectronics research more sustainable: environmental assessment of an academic cleanroom

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Abstract

Research facilities with a focus on microelectronics hold potential for supporting a cleaner digital transformation. Their stringent work conditions in cleanrooms, however, are barely studied from an environmental perspective other than their energy efficiency. The goal of this paper is to quantify the environmental impacts of a case-study cleanroom dedicated to research on microelectronics. The life cycle assessment methodology was applied with a focus on the cleanroom's operations. As expected, a contamination-free environment has a high energy demand (4,400 kWh/m^2) that generates 56% of the facility's impact on global warming and 97% on fossil resource scarcity. Purchasing renewable energy can halve the carbon emissions of cleanrooms. However, our study also shows that untreated air emissions, and the consumption of gases and metals are major areas of concern. We encourage researchers to investigate new ways of recovering metals from their processes, especially critical raw materials, that may later be translated into larger-scale strategies for the microelectronics industry. In addition, optimizing and sharing the use of the facilities with more institutions can be the way forward to preventing the construction of additional academic and industrial cleanrooms. Academic cleanrooms may then become a lighthouse for circular and less harmful electronics.

Keywords: life cycle assessment; microelectronics; industrial ecology; critical raw materials; digitalization

Nomenclature

LCA	Life cycle assessment
EU	European Union
ISO	International Organization for Standardization
HVAC	Heating, Ventilation, and Air Conditioning

1. Introduction

Current global market trends and policy programs are spurring the rise of digitalization in all areas of life. In this line, the EU's Digital Decade lays down mechanisms to "ensure all aspects of technology and innovation work for people" [1]. With digital transformation comes additional pressure on the environment, especially with regards to the semiconductor and microelectronics industries. Energy and critical raw materials are of particular concern, which put in motion, among others, the EU's Critical Raw Materials Act where digitalization is one of the target areas [2].

In this context, continuous academic efforts are essential to develop new technologies and processes that facilitate a digital transformation while safeguarding environmental goals. Similar to the microelectronics industry, research facilities with a focus on microelectronics hold potential for new technological developments but require specific work conditions that need to be further analyzed. Such is the case with cleanrooms.

Cleanrooms are necessary in the manufacturing of microelectronics to provide contamination-free conditions, thus controlling the concentration, generation and retention of

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airborne particles [3], [4]. This demands adhering to cleanliness requirements that depend on the type of product as defined in ISO 14644-1:2015 [4] in terms of temperature, humidity and pressure conditions. Therefore, it is widely acknowledged that semiconductor cleanrooms require urgent measures to reduce their energy demand [5], [6], but a complete life cycle assessment (LCA) shall shed light on the many environmental hotspots of cleanroom operations.

So far, the environmental assessment of semiconductor and microelectronics cleanrooms has focused on industrial facilities, and the data is rather heterogeneous. Levy et al. [7] and Kircher et al. [8] did study an academic cleanroom, but only considered energy use. A detailed account of the material and energy inputs and outputs of cleanrooms is scarce, and some attempts do not report life cycle impact indicators [9] or only focus on carbon emissions [10].

To support academic efforts towards sustainable digitalization, we analyzed the environmental impacts of the operation of a cleanroom dedicated to research on microelectronics. Our study applies the LCA methodology as defined in ISO 14040-44:2006 [11], [12] to the IMB-CNM-CSIC cleanroom in Barcelona, and informs the facility managers and similar cleanrooms about the peculiarities of a sustainable management of academic cleanrooms.

2. Methodology

2.1. Case study description

The cleanroom under study belongs to the Institute of Microelectronics of Barcelona (IMB-CNM-CSIC), which is recognized as a Singular Scientific and Technical Infrastructure (ICTS) by the Spanish Ministry of Science and Innovation and integrated into the MICRONANOFABS network. Its infrastructure includes an operational area of 1,500 m^2 dedicated to the development and application of innovative technologies in the field of microelectronics. It is a major institution with distinctive features in southern Europe. The facilities are located in the campus of the Autonomous University of Barcelona but are independent from on-campus infrastructure except for sewage.

The cleanroom includes over 150 process and characterization tools dedicated to micro- and nanofabrication and the open-access facility facilitates collaborative ventures for both domestic and international research entities. With silicon-based technology as its focal point, the facility houses specialized domains including optical and nanolithography, thermal processes, metallization, chemical vapor deposition, wet and dry etching, and ionic implantation. To do so, the cleanroom maintains constant contamination-free work conditions, i.e. a humidity of 45-55%, a temperature of 21ºC and a pressure of 15-25 Pa.

2.2. Goal and scope definition

This study evaluates the environmental impacts of operating the IMB-CNM-CSIC cleanroom over a year, taking 2023 as a reference. The functional unit is the operation of 1 m^2 of cleanroom over a year, which facilitates comparisons with similar research-based infrastructure. Comparing with an industrial cleanroom with mass fabrication of microelectronics is not advisable, as research-based cleanrooms perform a different function and thus produce little amounts of devices.

The system boundaries cover the operations of the cleanroom, whereas the construction and decommissioning of the infrastructure are not included (Fig. 1). The inputs to and outputs from the system illustrate the metabolism of the cleanroom to deliver research-based activities around micro- and nanofabrication, i.e., the consumption of electricity, water, metals, chemicals, gases and workwear, and the generation of solid waste, wastewater and emissions to air. The use and applications of the micro- and nanodevices are not considered, as they are product-specific and do not affect the operations of the cleanroom. Transport of all materials to the cleanroom and of the solid waste to their waste management destinations (i.e., recycling or incineration) is evaluated.

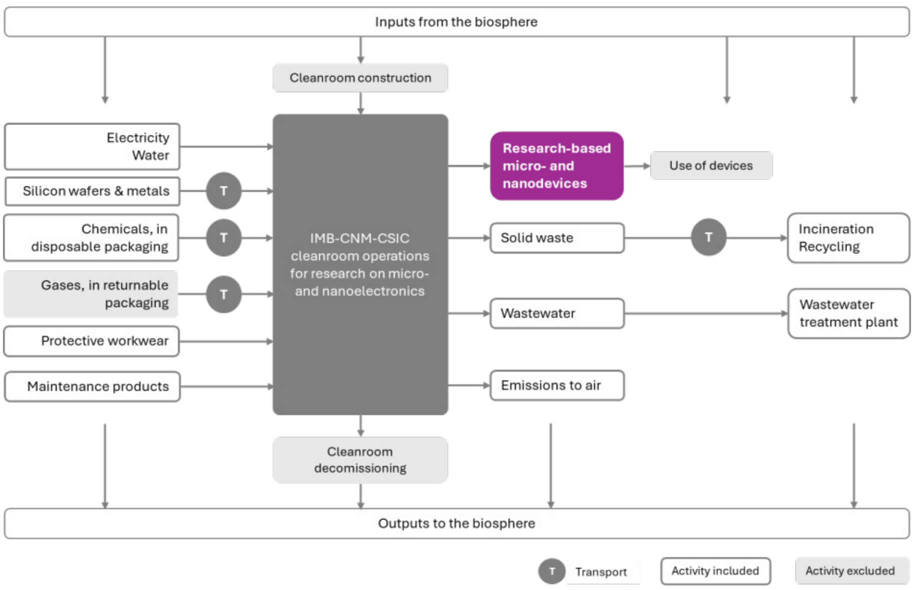

Fig. 1. System boundaries for the environmental assessment of the operations of the IMB-CNM-CSIC cleanroom

2.3. Life cycle inventory

A detailed data collection process was conducted to elaborate the life cycle inventory of the cleanroom operations (Table 1). This bill of materials relies on primary data obtained through the IMB-CNM-CSIC's management report and annual consumption records, such as energy and water bills and material purchase records. Interviews with the staff, on-site observations, weight measurements, and warehouse inventories complemented the quantification of the material flows. Background life cycle data were retrieved from the ecoinvent 3.10 database [13].

Energy and water flows are used across the facility, including the HVAC systems, lighting and technical equipment. Chemicals include acids, bases and solvents needed in a variety of steps of micro- and nanofabrications, which also need specialty gases. Expert input was needed to determine product compositions with complex applications and/or formulations, such as the buffered oxide etchant.

The research activities conducted at the cleanroom demand the consumption of silicon wafers and metals. As reported in the European Commission's EC's Raw Materials Information System [14], silicon, copper and titanium were listed as Critical Raw Materials in 2023, whereas aluminum was a Strategic Raw Material.

Maintenance products and protective workwear are essential to maintain the cleanliness levels of the facility. The consumption of sodium hydroxide and sodium chloride was included to account for neutralizing and cleaning products. Researchers, technicians and visitors must wear coveralls in order to avoid contamination. Reusable coveralls were not included, as they are used by a very limited number of people and are washed in an external cleanroom. However, the consumption of disposable gloves, face masks and overshoes is much larger given their recurrent use by the staff and external visitors, such as schools. The amounts were estimated considering the average number of visitors, which gave 28,800 overshoes, 14,400 face masks and 28,800 gloves.

In terms of distribution, the locations of the producers of all chemicals, gases and metals were identified through the product brands, and road transportation by truck was estimated using Google Maps. Chemicals are purchased in single-use containers that are recycled after each use. Gases, however, are supplied in returnable steel containers with an extended lifespan. In this case, only the transport was considered, thus excluding the production of the containers.

Finally, waste transport and management were assessed for each flow using the cleanroom's waste management report. Acids, bases and maintenance products were mixed with wastewater flows and sent to the on-campus sewer network that connects with a municipal wastewater treatment plant. Hazardous waste chemicals, such as toluene or ethanol, and the disposable workwear were sent to an incineration plant. Gas emissions are either neutralized by on-site scrubbers (e.g. ammonia or silane) or directly released into the air (e.g. carbon dioxide). Wafers and metals are assumed to be disposed of in landfills given the small dimensions of the research devices and the lack of recovery and recycling processes for these materials.

2.4. Impact assessment

The mandatory classification and characterization steps were conducted. To do so, the SimaPro 9.5 software was used in combination with the ReCiPe 1.08 (H) model [15]. The selected midpoint indicators were global warming, stratospheric ozone depletion, freshwater eutrophication, marine eutrophication, fossil resource scarcity and mineral resource scarcity.

2.5. Assumptions and limitations

All chemicals and gases are assumed to be produced and transported to the IMB-CNM-CSIC facilities from the supplier representative's nearest production plant. An important assumption is the management of gaseous emissions. The employed scrubbing systems are assumed to neutralize gases such as oxygen, argon or silane to 100% efficiency. The scrubbers are intended to catch and neutralize these specific gases, reducing any potential environmental damage from their discharge into the atmosphere. However, due to confidentiality agreements with the supplier, the eventual disposal of the scrubber cartridges, which contain remnants of the neutralized gases, could not be assessed.

Due to the lack of specific background data, some gases and chemicals were assimilated to products with similar structures as reported in ecoinvent 3.10 [13]. Examples include octafluorocyclobutane and tetrafluoromethane, which were modelled as tetrafluoroethylene.

2.6. Sensitivity analysis

A large body of literature has dealt with the energy efficiency of cleanrooms. Studies have assessed different energy models aiming to optimize pressure, temperature and humidity control and thus reduce a facility's energy demand [6]. The cleanroom under study went through an external auditing process that suggested a set of technological upgrades to reduce its electricity consumption. Beyond energy efficiency, however, research suggests that the geographical location of cleanrooms needs to be strategically studied to reduce their energy demand by benefitting from local climate conditions while adapting to future climate change scenarios [16]. For this reason, this study assessed the sensitivity of the cleanroom to varying the electricity mix. It does so by applying the electricity mix of four of the countries that dominate the semiconductor market (Taiwan, Japan, the United States and China) [17] and of three countries with minimum to no market share but high renewable energy production (Costa Rica, Switzerland and Norway).

Table 1 Life cycle inventory of the operation of the cleanroom for the year 2023. Data per functional unit (i.e., 1 m^2 of operational area)

	Material and energy flows	Quantity	Units	Waste management
Electricity	HVAC	3.9E+03	kWh	
	Operational equipment	3.9E+02	kWh	
	Lighting	1.3E+02	kWh	
Water		2.8E+00	m^3	To wastewater treatment plant
Chemicals	Acetic acid	8.8E-03	kg	To wastewater treatment plant
	Nitric acid	7.0E-02	kg	To wastewater treatment plant
	Hydrogen fluoride	1.6E-01	kg	To wastewater treatment plant
	Hydrochloric acid	3.8E-02	kg	To wastewater treatment plant
	Sulfuric acid	1.1E+00	kg	To wastewater treatment plant
	Phosphoric acid	3.8E-02	kg	To wastewater treatment plant
	TechniEtch Al80	1.1E-01	kg	To wastewater treatment plant
	Buffered oxide etchant	1.7E-01	kg	To wastewater treatment plant
	Hydrogen peroxide	3.7E-01	kg	To wastewater treatment plant
	Ammonia	9.7E-03	kg	To wastewater treatment plant
	Potassium hydroxide	1.3E-01	kg	To wastewater treatment plant
	Acetone	1.8E-01	kg	To incineration
	Isopropanol	1.4E-01	kg	To incineration
	Ethanol	5.3E-03	kg	To incineration
	Toluene	7.3E-03	kg	To incineration
	Propylene glycol	8.7E-03	kg	To incineration
	Lactic acid	2.7E-02	kg	To incineration
	Super Q	2.9E-02	kg	To incineration
	Microstrip 2001	7.5E-02	kg	To incineration
	Ethylene dichloride	1.4E-02	kg	To incineration
Gases	Carbon dioxide	1.3E-01	kg	To air
	Hydrogen	1.5E-01	kg	To air
	Oxygen	3.5E-01	kg	Neutralized in scrubbers
	Nitrogen	3.1E-02	kg	To air
	Helium	2.4E-02	kg	To air
	Argon	8.4E-02	kg	Neutralized in scrubbers
	Hexafluoroethane	4.0E-03	kg	To air
	Silane	1.3E-03	kg	Neutralized in scrubbers
	Hydrobromic acid	8.0E-03	kg	Neutralized in scrubbers
	Ammonia	1.8E-03	kg	Neutralized in scrubbers
	Boron trichloride	2.1E-03	kg	Neutralized in scrubbers
	Sulfur hexafluoride	3.3E-02	kg	To air
	Tetrafluoromethane	6.0E-02	kg	Neutralized in scrubbers
	Trifluoromethane	5.0E-03	kg	To air
	Dichlorosilane	3.0E-03	kg	Neutralized in scrubbers
Packaging	Disposable HDPE packaging for chemicals	1.1E-01	kg	To recycling
	Returnable steel packaging for gases	4.8E+00	kg	Reused
Silicon wafers & metals	100 mm Silicon wafers	1.8E-01	kg	To disposal
	Aluminum	3.3E-05	kg	To disposal
	Gold	1.5E-04	kg	To disposal
	Chromium	8.0E-06	kg	To disposal
	Copper	3.3E-04	kg	To disposal
	Titanium	1.7E-05	kg	To disposal
Protective workwear	Polypropylene overshoes & face masks	2.2E-01	kg	To incineration
	PVC gloves	9.6E-02	kg	To incineration
Maintenance products	Sodium hydroxide	2.7E+00	kg	To wastewater treatment plant
	Sodium chloride	1.3E+00	kg	To wastewater treatment plant
Transport	Transport to facility	1.5E+00	tkm	
	Transport to waste manager	1.5E-01	tkm	

3. Results and Discussion

3.1. Environmental hotspots of cleanroom operations

The results of the environmental assessment show four prominent hotspots in the operation of a cleanroom for research on microelectronics (Fig. 2):

- **Energy consumption**: the consumption of electricity accounts for 56-97% of the environmental impacts of the cleanroom. With a demand of about 4,400 kWh/m^2, the electricity use of the cleanroom results in the emission of 1,241 kg of CO_2 eq./m^2. 88% of these emissions are associated with Heating, Ventilation, and Air Conditioning (HVAC), as the contamination-free conditions must be maintained year-round. Besides the energy intensity, much of these impacts depend on the electricity mix. Catalonia's electricity is predominantly sourced from nuclear energy (56%), natural gas co-generation and combined cycle processes (27%), with only 16% from renewable sources such as wind and solar power [18]. This also translates into contributions of 88% and 97% to the fossil resource scarcity and mineral resource scarcity, respectively.

- **Direct emissions and waste management:** global warming (42%) and marine eutrophication (27%) are largely affected by direct gas emissions and wastewater management, respectively. A group of gases is released into the atmosphere without further treatment with scrubbers, which include carbon dioxide (CO_2), hydrogen (H_2), nitrogen (N_2), helium (He), hexafluoroethane (C_2F_6), ethylene (C_2H_4) and sulfur hexafluoride (SF_6). The high global warming potential of some of these gases turns them into critical hotspots in the environmental management of the cleanroom's direct emissions. For instance, a perfluorinated compound used in plasma etching such as SF_6 has a global warming potential of 26,100 kg CO_2 eq. per kg of SF_6 [13]. Contributions to marine eutrophication are due to the wastewater treatment process, which involves mixing wastewater with various chemicals and gases and neutralizing them with sodium hydroxide.

- **Consumption of gases:** producing process-specific gases contributes 28% of the impact on ozone depletion. More than 95% of this impact is caused by the production of tetrafluoroethylene (C_2F_4), which is assimilated to tetrafluoromethane (CF_4) due to data constraints. C_2F_4 and CF_4, though similar in their fluorine content, exhibit substantial differences in their production processes and emission profiles. C_2F_4 is primarily generated through the pyrolysis of chlorodifluoromethane and is widely used in manufacturing fluoropolymers, such as Teflon. Conversely, CF_4 is a byproduct of aluminum smelting and plays a significant role in semiconductor manufacturing for plasma etching processes. Both compounds have high ozone depletion potentials, and CF_4 is particularly notable for its extreme persistence in the atmosphere.

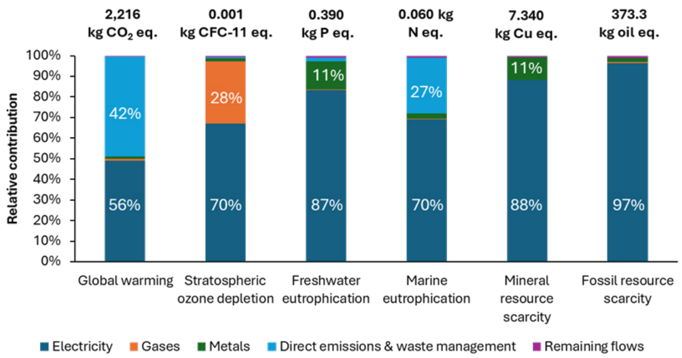

Fig. 2 Contribution analysis of the cleanroom's operations

- **Consumption of metals:** 11% of the impacts on mineral resource scarcity and freshwater eutrophication are related to the extraction and use of minerals. Gold mining is particularly relevant in the system, even if only 1.5E-04 kg of gold are used per m^2 of cleanroom. Although it has not been listed as Critical Raw Material so far, the extraction of gold is associated with energy-intensive processes and emissions to water bodies resulting from sulfidic tailings, among others.

3.2. Sensitivity to the electricity mix

The results are highly sensitive to the electricity mix applied in the cleanroom to run the facility (Fig. 3). This shows that the IMB-CNM-CSIC cleanroom can take advantage of a greener electricity mix to reduce its environmental impact. It also demonstrates that the current semiconductor market is not strategically located in regions with a high share of renewable energy. If an identical cleanroom with the same operational parameters were connected to an electricity provider in countries such as China or Taiwan, the CO_2 equivalent emissions would at least double. In contrast, applying an electricity mix with the share of renewables of Costa Rica, Norway or Switzerland could even halve the CO_2 emissions of the cleanroom.

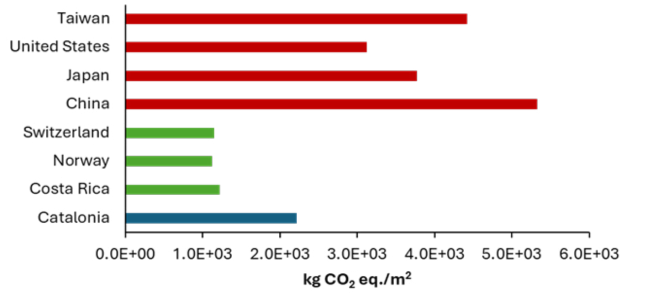

Fig. 3 Sensitivity of global warming emissions to the national electricity mix

4. Conclusions

To the existing pool of more than 420 semiconductor manufacturing facilities in the world, at least 73 more will join within the next four years [19], [20]. The EU holds currently 10% of the global semiconductor production capacity, and aims to double it by 2030, as stated in the 2023/1781 European Chips Act [21]. The pressures and impacts of the micro- and nanoelectronics industry will thus keep rising, and urgent efforts are needed to reflect and rethink how cleanrooms are managed. The academic cleanroom under assessment shows evidence of where we stand and what kind of research and industrial actions could reduce their environmental footprint.

The IMB-CNM-CSIC cleanroom shows four hotspots:

(1) As expected, energy use accounts for 56-97% of the environmental impacts. In the short term, we encourage cleanrooms to urgently switch to renewable energy sources next to their current efforts to improve the energy efficiency of their processes.

(2,3) The production of fluorinated gases and their untreated emissions to the atmosphere is still a critical issue for global warming and ozone depletion. After many years of environmental advocacy, we show that there is still work to be done to minimize their use and to neutralize their direct emissions.

(4) Although academic cleanrooms do not serve productivity purposes, their consumption of minerals and critical raw materials needs to be urgently considered. We show that small quantities of gold (1.5E-04 kg per m^2 of cleanroom) contribute to 11% of mineral resource scarcity. We expect this impact share to increase dramatically if the facility's energy demand is reduced.

Realizing this improvement potential necessitates new approaches to cleanroom research and a radical shift in the micro- and nanoelectronics industry. We propose the following actions to support this process:

- Conducting more research on the workflows of specific technologies to identify the sources of energy, gas and material use, waste and direct emissions. Technical assessments of individual processes and technologies along with mass balances can shed light on energy efficiency practices and circular resource management within cleanrooms.
- Targeting new ways of recovering metals from academic cleanroom processes. More recycling is needed at the manufacturing stage (not only through e-waste recovery) to reduce vulnerabilities and disruptions in the supply chains. Supporting the recovery and recycling of critical raw materials, which typically have very low recycling rates, is essential.
- Optimizing and sharing the use of the facilities with more institutions. This can also be the way forward to preventing the construction of additional academic and industrial cleanrooms. As our study shows, there is an abundance of cleanrooms in countries that mainly produce electricity from fossil resources and thus increase our global environmental impacts. Strategically debating the actual need and location of new cleanrooms is encouraged.

Although academic facilities contribute to society with new technologies that can support the digital transformation, it is of paramount importance that they also account for the costs of such efforts. In doing so, academic cleanrooms may then become lighthouses for circular and less harmful electronics.

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