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Navigating Trends and Ecological Sustainability Needs in Germany and Europe's ICT Industry

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Abstract: The Information and Communication Technology (ICT) industry significantly impacts the environment across various life cycle stages, including material sourcing, energy use, and waste. To mitigate these effects, the German Ministry for Education and Research established the Competence Center Green ICT @ FMD, focusing on applied research to reduce the environmental footprint of ICT technologies. This paper identifies five emerging areas within the microelectronics sector that are key for ecological sustainability and the economic future in Germany and Europe to address the negative environmental impact of the rapidly growing demand of ICT: (i) Circularity in microelectronics, (ii) Green data centers, (iii) Green power electronics, (iv) Green quantum technologies, and (v) Green procurement and supply chains. These areas were identified through a systematic approach involving surveys, expert interviews, roadmap analysis, literature review, and market research. Criteria such as geographical relevance, time-related relevance and leverage were used to assess the feasibility of each area. Circularity in microelectronics addresses resource efficiency and product lifetime extension, while green data centers focus on hardware, software, and infrastructure optimization to reduce environmental impact. Green power electronics aims to enhance energy efficiency in critical sectors like electromobility and data centers. Green quantum technologies explore innovative applications in sensors and chemical processes, and green supply chains emphasize reducing CO_2 emissions throughout value chains.

Introduction

The information and communication technology (ICT) industry is one of the fastest growing industries and is linked to numerous environmentally critical aspects across all life cycle stages (OECD, 2024). These include the sourcing of critical raw materials, the use of toxic substances, as well as water, resource, and energy consumption during production. Moreover, significant energy consumption during the usage phase and a lack of recyclability contribute to non-compliance with circular economy principles.

To reduce the environmental impact of ICT, the German Ministry for Education and Research established the Competence Center *Green ICT @ FMD*[1]. The center's current focus is on conducting applied research to reduce the carbon footprint and environmental impact of sensor, edge computing, and cloud systems, communication infrastructures, and the production of microelectronic components. Nevertheless, many other technologies fall under the umbrella of ICT, and there are numerous tangential topics of future relevance that are not yet addressed by the competence center. Therefore, an additional key task of the competence center is to identify emerging areas of interest beyond the three already mentioned, to ensure long-term sustainability and innovation in these sectors.

In this paper we introduce five emerging areas in the context of microelectronics and evaluate their feasibility based on different criteria, such as industrial demand and leverage in Germany or Europe, and ecological urgency.

[1] https://greenict.de/en/

Methods

To identify the topics, we conducted different steps, summarized as follows:

1. Development of a Questionnaire
2. Expert Interviews and Roadmap Analysis
3. Identification of Emerging Topics
4. Literature Review, Market Research, and screening of Funding Programs
5. Evaluation of the findings
6. Validation with Experts

We first created a comprehensive questionnaire to assess the current structure in the competence center and ensure demand-driven development aligned with industry needs. This questionnaire evaluated the relevance of the current three topics sensor, edge and cloud systems, communication infrastructures and microelectronics production. The survey includes additional elements to identify further topics, for instance on which inquiries were received from the industry, but could not be covered by the current research focus. Also, we included future research topics that the consulted experts suggested emerging from their current research fields.

In the second step, we conducted interviews with industry and academic experts. The interview was supplemented by a composed questionnaire. Additionally, we reviewed green ICT-relevant roadmaps specified to microelectronics to align with future trends and opportunities.

Insights from the questionnaires, expert interviews, and roadmap analysis were consolidated to identify key topics requiring attention in sustainable ICT microelectronics.

After specifying our key areas, we conducted a literature review and market analysis to break down the identified topics into subtopics.

The identified topics and subtopics were evaluated based on their feasibility within the existing technological and industrial environment. Criteria included industrial demand, ecological urgency, and ecological potential. This evaluation was based on our findings from market research, literature review and an additional screening of funding programs on the German and European level.

In a last step, we verified the completeness of the identified topics and subtopics through consultations with additional experts in the respective fields. This step ensured a comprehensive assessment.

Results

We identified five key emerging areas in the microelectronics sector: (i) circularity in microelectronics, (ii) green data centers, (iii) green power electronics, (iv) green quantum technologies, and (v) green supply chains. The areas and their assessment in terms of geographical and temporal relevance and leverage are summarized in Table 1 and discussed further in the following sections.

Area	Time relevance	Geographical relevance (GER, EU)	Leverage
Circularity in Microelectronics	**very high**	**very high**	**very high**
Circular design approaches			
Reduction of chemicals, gases, energy and materials			
Reduction & substitution of chemicals, gases and materials			
Ultrapure Water reuse and recycling			
Reliability			
Extension of product and component lifetime through reuse, repair, refurbishment and remanufacture			
Recycling			
Green Data Centers	**very high**	**high/very high**	**high**
CPU			
GPU			
AI-Acceleration			
Advanced Packaging & Memory			
Alternative storage medium			
Chip-Level-Cooling, Board-Level-Cooling			
Neuromorphic Computing			
Load Managment			
Virtualisation			
Power & performance measurment and benchmarks			
Water consumption			
Waste heat utilisation			
Alternative cooling technologies			
Power supply units			
Green Power Electronics	**high**	**very high**	**high**
Increasing power density through miniaturisation by using WBG and UWBG semiconductors			
Further development of ultra-low-power circuit technologies			
New circuit concepts and topologies			
New components and circuit architectures for the efficient support of AI algorithms			
New packaging			
Cognitive power electronics			
Alternative cooling technologies - direct liquid cooling			
Life cycle assessment, eco-design, cycle management and increased reliability			
Green Quantum Technologies	**medium**	**high**	**medium**
Q-accelerators can be used in data centers (QC-HPC) and possibly Q-coprocessors			
Hardware-Software Co-Design			
Life cycle assessment			
Upgradeable Hardware infrastructure (QPU) and reusable peripherals			
Substitution of toxic materials and components			
Closed cryogenic cooling circuits			
Green Procurement and Supply Chains	**high**	**high**	**high**
Quantification of GHG emissions from materials, components and systems along the value chain			
Evaluation of emission reduction options, e.g. energy efficiency & material reduction potentials			
Determination of measurable and achievable improvements through eco-design			

Table 1. Identified Key Areas and Their Time-Related Relevance, Geographical Relevance, and Leverage.

Circularity in Microelectronics

Circularity in microelectronics encourages the efficient use of resources by extending the product and component lifetime through reuse, repair, refurbishment and recycling at the end-of-lifetime. It also encompasses circular design approaches, increasing material efficiency and minimizing environmental impact throughout the entire value chain.

Integrated circuits (ICs) are among the most environmentally critical components in ICT, as their production is energy-intensive and involves numerous toxic chemicals (Boyd, 2011). As an example of circular economy practices within the ICT sector, the reuse of ICs represents a notable opportunity to reduce the environmental footprint of chip manufacturing. Due to the significant economic value of ICs, reuse provides a technique to prolong the lifespan of valuable components while also easing constraints on semiconductor supply chains. Nevertheless, further research is necessary to advance recovery technologies and standards, conduct a comprehensive life cycle assessment as well as to establish appropriate market incentives, in order to facilitate the reuse of ICs (Stoddard, 2024).

If lifetime extension is not possible, responsible disposal and recycling are essential to recover valuable materials (e.g. copper and palladium). Although ICs play an extensive role as they contain valuable and critical materials, it is also important to consider other parts of ICT devices. This will help to mitigate the impact of the growing demand for ICT and reduce overall material consumption, while taking into account the criticality of these materials in terms of their strategic importance and scarcity, as outlined in the list of critical raw materials (European Commission, 2025). However, e-waste is a highly complex and heterogeneous waste. At present, only a few precious elements present in integrated circuits are recovered by current recycling techniques, such as silver, gold, palladium and copper (Umicore, 2025).

Circularity is also crucial in ultrapure water (UPW) reuse and recycling to reduce the water footprint since major semiconductor factories require up to 99 million liters (L) of water per day for cooling and cleaning during manufacturing (TSMC, 2021, Den et al., 2018). Moreover, the development of more efficient material deposition processes, the utilization of more environmentally friendly chemicals, and the incorporation of exhaust gases or fluids within the fabrication process have the potential to address the significant impact of fluorinated gases in manufacturing, which account for 80–90% of direct emissions in industrial facilities and possess a high global warming potential (Raoux, 2021).

Recent technological advancements, including 3D printing for microelectronic devices and bio-based materials for packaging, are being investigated and developed with the objective of enhancing the circularity of ICT components (Zhang et al., 2025, Raskin et al., 2023). Nevertheless, it is essential to undertake additional fundamental and practical research on materials, in addition to conducting a comprehensive life cycle assessment.

In recent years, the European Union has implemented several legislative frameworks promoting circular economy practices such as the Circular Economy Action Plan (European Commission, 2025). To comply with these frameworks, the ICT sector must adopt circular economy approaches.

In addition to the present legislative pressures, it is inevitable that there will be an increased demand in the long term for the ICT sector to reduce its overall environmental impact throughout its entire value chain, in relation to the growing consumption of ICT (Wang and Chiu, 2014).

Overall, the issue of circularity in microelectronics is becoming increasingly important in order to address the scarcity of raw materials and the global dependency and bottlenecks on these resources in order to strengthen Europe's sovereignty.

Green Power Electronics

As electrification of the automotive and energy sectors will further play a key role in decarbonizing our society, power electronics will be crucial. Consequently, the power electronics market is projected to grow at a CAGR of 7%, increasing from a market value of $28.89 billion in 2023 to $35.7 billion by 2029 (Yole, 2024).

Power electronics involve various metallic raw materials such as aluminum and copper, presenting significant environmental improvement opportunities. Thus, currently a particular ecological focus lies on circular economy principles, emphasizing reuse and recycling, which result in reduced use of critical raw materials, extended product lifetimes and enhanced reliability (Huber et al., 2024, Sangwongwanich, 2024).

Another approach of reducing the use of new critical raw materials is via increasing material efficiency through miniaturization of wide bandgap (WBG) semiconductors, e.g. SiC and

GaN. The miniaturization of converter systems and increased power density enabled by these semiconductors lead to substantial savings in copper and aluminum (ECPE, 2018).

However, the selection of material poses a sustainability challenge. While silicon carbide (SiC) results in lower losses and energy consumption during use, its production is associated with significantly higher environmental impacts (Morra, 2024). At the same time, SiC and GaN devices are significantly more efficient in operation than silicon components (Mishra, 20239. Therefore, a comprehensive comparison of different technologies necessitates detailed life cycle assessments for accurate conclusions.

Promising technological trends in the long term, although still requiring further research, include ultra-wide bandgap semiconductors such as Ga_2O_3, AlGaN, AlN, or diamond (Xu et al., 2022). These materials exhibit excellent electrical characteristics but are not yet market-ready. Specifically, advancing research on switching characteristics of materials like Ga_2O_3 is essential to enable future competition with silicon (Si), SiC, or GaN (Yole, 2024).

Packaging in power electronics is also undergoing transformation. With decreasing semiconductor prices, the focus is shifting from the smallest chip size to other trends. This shift involves integrating functions into single components, especially for wide bandgap components, drivers, sensors, and capacitors, leading to new assembly and connection techniques.

Digitalization and artificial intelligence can facilitate cognitive power electronics concepts that expand traditional power electronic functions through new sensor and motor functionalities. This intelligent power electronics can lead to significant energy savings at the system level as functions of separate components are integrated into a single system (Köllner, 2024).

Overall, power electronics are an essential and well-established pillar of the European semiconductor industry, with 25% of global power electronics originating from Europe (Grand View Research, 2023). Therefore, the geographical and timely relevance is very high, as a sustainable transition of the power electronics markets can significantly enhance the competitiveness in the global market through innovation and ecological sustainability.

Green Data Centers

The rapid adoption of technologies like AI and 5G, along with an increase in digital services, is expected to significantly boost data volume in the coming years (IEA, 2024). This increase will lead to higher electricity consumption by data centers, with estimates indicating a 54% rise in energy use from 2023 to 2033 in Germany alone (Stobbe et al., 2024).

Green data centers require advancements in hardware, software, and infrastructure. Key hardware focuses include GPU, CPU, and AI (Yole, 2022) acceleration while software improvements should target load management and virtualization (Leiserson, 2020). Infrastructure considerations must address water consumption, waste heat utilization, cooling technologies, and energy supplies (Aslan et al., 2025)

Innovations in CPU acceleration are critical, with advancements like increasing core counts, new processor architectures, and modern memory technologies (e.g., DDR5 and PCIe5). Additionally, chiplets present potential benefits but face challenges due to non-standardized interconnects, necessitating research into application-specific connections.

The demand for AI accelerators is growing for both inference and training, driven by AI application and further technologies including photonics, neuromorphic, and quantum computing (McKinsey, 2024). For more efficient data transmission in AI applications, silicon photonics stand out for their ability to reduce energy consumption in data transmission (Yole, 2022).

In networking, the use of smart Network Interface Cards (NICs) and Data Processing Units (DPUs) is increasing, alongside the disaggregation of data centers through DPU processors and the deployment of passive optical and point-to-point networks.
In advanced packaging and memory, innovations such as Through Silicon Via (TSV), chiplets, and 2.5D-3D packaging are becoming essential as the pace of advancements slows (Yole, 2022).

As a notable amount of resource use and GHG emissions is due to the production of IT hardware (Busa and Hegemann, 2019), it is also key to focus on circularity aspects and product lifetime increasing measures for data centers and IT hardware (Hoosain et al., 2023). These include numerous circularity approaches including hardware refurbishment, component reuse, recycling of critical parts, and modular systems.
With increasing performance of computing systems, direct-to-chip cooling and board-level cooling strategies are being explored, focusing on waste heat utilization and energy harvesting (Brady, 2024, Forschungszentrum Jülich, 2024). On infrastructure level efficient waste heat utilization and alternative cooling methods, such as immersion cooling, are crucial (Hintemann et al., 2024, Geary, 2024).

Additionally, research into new storage solutions, including glass-based (Anderson, 2025), ceramic-based, and DNA-based storage technologies (Fraunhofer INT, 2020; Beil, 2021, is ongoing, potentially offering significant advantages in efficiency and capacity. Nevertheless, these technologies are currently not commercially available and still at an earlier technological readiness level (TRL).

Green data centers are increasingly important for Germany and the EU, as their geographical advantages attract more data center operators (Hintemann et al., 2024). Additionally, numerous regulations emphasize energy efficiency and climate neutrality commitments. Hence, focusing on green data centers is not only necessary to meet sustainability goals, it is also a locational advantage for Europe in global competition.

Green Quantum Technologies

The fourth area focuses on green quantum technologies. Potential applications for quantum technologies (QT) include the creation of more efficient sensing, simulation, computing and communication. The application fields for QT are diverse, encompassing navigation, precise measurements, data storage, material research, artificial intelligence, biotechnology, medical applications, as well as quantum cryptography and communication.
Quantum technologies are based on the principles of quantum mechanics, providing higher computing power and more energy-efficient operations compared to current computing.

The manufacturing of individual components and assembly processes for QT are energy and material intensive. Therefore, it is essential to develop sustainable solutions for the production and operation of quantum technologies to minimize environmental impacts. A more sustainable use could be achieved through the adoption of renewable energy sources and by optimizing the use of materials.
Opportunities for green quantum technologies include waste heat utilization, usage of more environmentally friendly chemicals and materials, energy efficiency, recycling, and cooling solutions.

The integration of quantum technologies with enabling technologies has the potential to yield substantial advancements. An optimized hardware-software co-design results in enhanced performance and energy efficiency of quantum technologies and their applications. Furthermore, Q-accelerators offer the potential to enhance performance and energy efficiency in data centers.

However, challenges remain. The energy accounting and predictions for future quantum technologies require a comprehensive understanding including life cycle assessment of the fundamental components and foundational technologies is required.

Quantum technologies are becoming increasingly important on a global scale (Riedel, 2019). The quantum computing market is expected to grow at a compound annual growth rate (CAGR) of 56.0% to USD 64,988.3 million between 2020 and 2030 (Research and Market, 2020). While this area is heavily dependent on the continued advancement of quantum technologies and their applications, it offers considerable potential for disruptive innovation (Coccia, 2022). Europe has a strong starting position in the global innovation competition, with half of all scientific publications and approximately 40% of researchers in the quantum computing field originating from Europe (VDI Technologiezentrum GmbH, 2022). To maintain Europe's current position in this cutting-edge sector, Europe must continue to invest in knowledge-based industry and technology. Given the anticipated operationality of many QTs in the upcoming decades and the rise in financing for quantum innovation, now is a critical time to address ecological sustainability and influence the direction of quantum innovation (Root, 2025).

Green Supply Chains

The fifth area, focusing on environmentally friendly procurement and supply chains, involves quantifying greenhouse gas emissions and assessing opportunities for emissions reduction throughout the entire value chain. Sustainable procurement enhances transparency regarding the environmental impact of components and aids companies in making informed decisions about sustainable practices.

While there will be tremendous predicted growth of the ICT sector, it faces several challenges, including highly complex and opaque supply chains, resource planning under uncertainty, unpredictable fluctuations in demand, and global crises. In the microelectronics industry in particular, supply chains are highly complex, involving numerous players from all over the world. It is therefore essential to optimize the design of the logistics network and use environmentally friendly transport methods, even though these long-term measures require additional investment and may result in higher costs in the short term.

Supplier and material selection can help to increase transparency, mitigate risks, and ensure responsible production in the long term and can serve as an incentive mechanism for producers to manufacture under socially and environmentally better conditions. Increased transparency can further reveal opportunities for emissions reduction, through energy efficiency and material optimization.

Overall, green supply chains are becoming increasingly important due to the global supply chains of the microelectronics industry and regulatory obligations in the EU relating to ESG requirements and supply chains, such as the European Corporate Sustainability Due Diligence Directive (CSDDD) (European Commission, 2025, European Commission, 2024). Combined with circular economy approaches, green supply chains represent a key opportunity for environmental sustainability and help reduce dependence on raw material suppliers, contributing to Europe's technological sovereignty. As a result, both geographic and time relevance are considered high.

Conclusions

The ICT sector is growing rapidly, but also has a significant environmental impact that must be taken into account in all life cycle phases.

Our research emphasizes the importance of (i) Circularity in Microelectronics, (ii) Green Data Centres, (iii) Green Power Electronics, (iv) Green Quantum Technologies and (v) Green Supply Chains. While these areas have a particularly high potential for environmental improvements, they are also vital for Europe's technological sovereignty and competitiveness in the global market in the future. Therefore, it is essential to address both environmental and economic challenges.

To shape a more economically and ecologically sustainable future, it is particularly important to foster collaboration between industry, research organizations and policy makers in Europe to develop innovative solutions and create the necessary framework conditions. As many of these areas are interrelated, it will be crucial that different sectors collaborate on implementing sustainable practices and solutions.

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