The role and challenges of microelectronics in enabling the future of computational techniques, numerical approaches and AI

Olivier Bonnaud
IETR Dept. OASIS, University of Rennes,
GIP-CNFM National Coordination of Microelectronics Education,
MINATEC – Grenoble INP,
3 Parvis Louis Néel, 38016 Grenoble,
France

Received: December 11, 2025. Revised: April 12, 2026. Accepted: May 13, 2026. Published: July 6, 2026.

Abstract-Global digital approaches are evolving rapidly in our society. This development appears very useful in a wide range of applications, but it also leads to a considerable increase in the amount of data transferred and processed, more particularly due to Artificial Intelligence (AI) tools. Given that all operations in this field are primarily based on electronic equipment, this consequence is an exponential growth in electrical energy consumption. Within the next decade, this could lead to a deleterious global lock-in. Thus, the microelectronics sector has become a global priority and societal behaviors and technologies must evolve. To achieve this, new skills and know-how are needed to stimulate innovation, corresponding to new jobs in microelectronics. Recent research results predict that the energy consumption of all hardware can be reduced by a factor of 10. By combining software simplification, edge computing, and library minimization for AI, we can hope to meet the challenges.

Keywords-Digital world, microelectronics, energy consumption challenge, innovation, skills and know-how, engineering training

I. CONTEXT TOWARDS THE CHALLENGES

Computing techniques, digital approaches, and artificial intelligence (AI) are evolving rapidly in our society. This development seems to be very useful for some of our daily activities in a wide range of applications or in the field of research and development. The main hardware of this domain is based on connected objects with their electrical energy supply environment and their transmission equipment, such as metal-based wires, optical fiber cables, wireless transmission tools, satellite transits, etc. It is clear that connected objects, included in the Internet of Things (IoT) domain, are generating a lot of data to transfer, the application domains covering a very large part of societal activities (communications, health, environment, industry, entertainment, security, etc.). The number of connected objects is growing exponentially, and thus has been inducing a huge increase in data generated and treated over the last two decades, [1]. This evolution seems to continue with the very fast growth of AI. Figure 1 shows the expected evolution for the next decade. The number of IoT devices grows by a factor of 2 every 5 years. The amount of data could reach YB (Yotta bytes) by 2036, with a growth rate of a factor of 10 every 6 years.

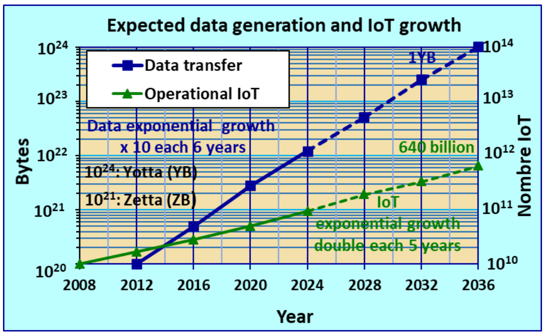

Fig.1 Evolution of generated/transferred data during the last two decades and expected evolution for the next decade
Source created by the author.

Given that all operations in this field are mainly based on electronic equipment and tools, this technical field is driving exponential growth in energy consumption, mainly electrical, [2]. If this trend is not significantly modified, it could lead, within a decade, to a deleterious global lock-in, with digital activity absorbing the entire global production of electrical energy.

Figure 2 illustrates this trend by comparing the growth in global electrical energy consumption with that of digital activities, which are becoming increasingly dominant.

Total annual electrical energy consumption is converging with that of the digital world, which is growing exponentially, [3]. It is clear that the electrical energy consumption of the digital world is set to increase dramatically, to reach, without any change, a level higher than the current global energy production of any kind. As a mandatory result, societal behaviors and technologies must change and evolve in the short term.

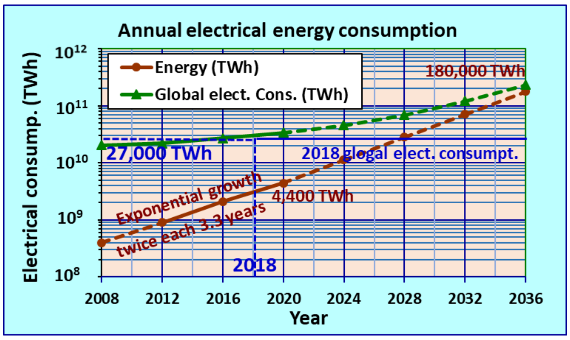

Fig.2 Expected evolution of the global electrical energy consumption assuming the same trend of the IoT expansion

Source created by the author.

II. ROLE OF MICROELECTRONICS IN THE NUMERICAL DOMAIN

Because electronics are at the heart of all equipment, the microelectronics sector has become a global priority, and fortunately, recent research results predict that the energy consumption of all hardware will be reduced by a factor of more than 10. Many approaches can be applied in this way.

A. *Software and data transmission challenges*

The first one that aimed more at specialists in computer science and applied mathematics, consists of finding new algorithms and mathematical solutions that could significantly reduce the size of the code. Even if some improvements are permanent in the power of calculation and the size of the memories and calculators, unfortunately, the decrease in the power consumption remains marginal (in the range of percent).

Another aspect concerns data transmission. The development of the cloud, which makes it possible to increase the size of distributed memories, requires large data transfers and, consequently, high energy consumption. While fiber optic transmission minimizes energy losses when transmitting to local servers, long-distance transmission requires very high energy consumption in order to amplify the optical signal over thousands of kilometers, as in the case of intercontinental undersea communications, [4]. Improvement of high-power electrical converters must be performed, as well as electro-optical amplifiers. The total optical signal amplification for an 8,000 km long fiber optic cable is about 10^{400}. Decreasing to 5% the losses of the power electrical converters from high voltage (around 20 kV) to low voltage (several Volts) for 100 amplifiers could save tens of megawatts for each optical fiber cable. The problem is mainly at the level of the microelectronics field.

Another area of consumption today is AI systems, which process billions of pieces of data and also require enormous energy consumption for each search in digital libraries or data centers. For the year 2022, the consumption attributed to only AI set-in was evaluated to 460 TWh. In 2026, the estimated consumption is estimated to be 1,000 TWh with an equivalent exponential growth rate for the following years! Energy efficiency per artificial neuron is still well below that of natural biological neurons. The ratio of power consumed is seven orders of magnitude higher, which represents a huge margin of progress compared with the human brain. The development of neuromorphic circuits seems to be an interesting way of minimizing the consumption of neural electronic circuits, which can save a lot of computation in the context of AI.

By combining software simplification, edge computing, local signal processing, and library minimization for AI, we can hope to meet the challenges.

B. *Microelectronic components and circuits*

Even if it is not visible for the classical users, the hardware part of each connected object, each computing tool, each server, and each data center contains billions and billions of elementary devices. The integration by decreasing the size of the elementary devices (mainly the transistors) allowed that fabulous evolution, [5], [6]. However, decreasing the size of elementary devices close to atomic distance (nanometers) generated new phenomena in the device involving quantum physics effects, such as the tunnel effect. These phenomena are due to losses and leakage currents between the elementary regions of each component. The final result is the creation of permanent losses that occur by billions in a classical microelectronics circuit. For example, in a synchronous technology, the permanent leakage current can be much higher than the current involved in the calculation phase.

The main objective of microelectronics engineers is therefore to avoid leakage currents and permanent losses. Thanks to the extensive research carried out by research laboratories and corporate R&D departments over the last few decades, many solutions are now available.

III. IMPROVEMENT OF MICROELECTRONICS DEVICES AND SYSTEMS

After several years of research, many solutions have been identified to improve the energy consumption efficiency of electronic circuits and systems, mainly involved in the IoT.

A. *Electronic circuit families*

The first point concerns microelectronic circuit technologies. The gradual transition from synchronous to asynchronous technology, and the increase in the proportion of analog electronics for many of the functions involved in the neuromorphic approach, should significantly reduce total losses. In addition, modifying the architecture of circuits that can control the standby of electronic functions not useful for computation can significantly reduce non-useful operations and therefore power consumption. Note that the human brain is well-suited to this approach.

B. Elementary device processes

The second point concerns elementary devices. The use of new materials, such as wide-bandgap semiconductors, can considerably reduce leakage currents. For example, SiC (silicon carbide), GaN (gallium nitride), and GIZO (gallium indium zinc oxide), [7] are good potential candidates, thanks to their relatively wide bandgap compared with the silicon used in silicon-based VLSI technologies, [8], [9]. The introduction of a high permittivity insulator, such as HfO_2 (hafnium dioxide), greatly reduces the tunnel leakage current by increasing the thickness of the ultrathin gate film for the same electrostatic effect in the channel of a MOS transistor.

C. Architecture of circuits and packaging

The third point deals with the introduction of 3D architecture at the level of elementary devices as well as the stacking of chips. This approach allows minimizing the losses of the interconnection tracks by decreasing significantly the length of the bonding wires and metal tracks. The use of chiplets with dedicated functions that are integrated in the same package allows a better optimization of each sub-circuit, [10]. The last example, but not the least, is the introduction of neuromorphic architectures that are better adapted to AI functions by minimizing the number of calculation steps of the computing phase for the sorting of data. Figure 3 summarizes the different approaches.

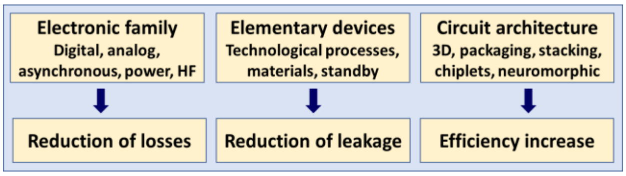

Fig.3 Different approaches in microelectronics to reduce electrical energy consumption of IoT
Source created by the author.

If the evolution responds to these needs, the expected evolution of the electrical energy consumption should follow the curve shown in Figure 4.

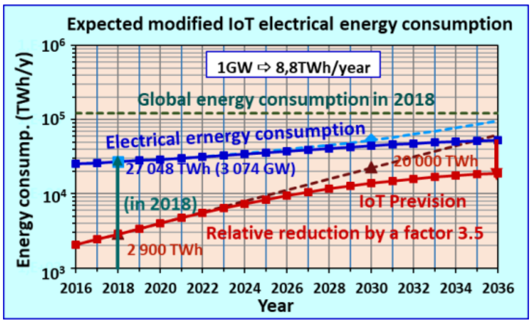

Fig.4 Evolution of global electricity consumption over the next decade. Digital/IoT power consumption will not exceed 20,000 TWh
Source created by the author.

If the targets are reached, the total consumption should be lower than the global electrical consumption of 2018 by 2036.

IV. SKILLS AND KNOW-HOW IN MICROELECTRONICS

To achieve this, new skills and know-how are needed to drive innovation in the production of billions of connected objects worldwide every year. This means new jobs, mainly in microelectronics.

The national network, in the form of a Groupement d'Intérêt Public (GIP), is called “Coordination Nationale pour l'Enseignement Supérieur en Microélectronique et Nano-technologies” (National Coordination for Higher Education in Microelectronics and Nanotechnologies), and comprises 13 partners, 12 academics, and an industrial union representing companies in the field, [11]. The GIP's mission is to offer the national academic and industrial microelectronics community the opportunity to acquire know-how in the 12 inter-university microelectronics centers. 7 clean rooms, 100 technical platforms covering all specialties, and national CAD services providing licenses for the main microelectronics design software are accessible. Every year, some 20,000 students and employees are trained, representing some 900,000 hours of study.

The GIP's strategy is to update the content of its activities in line with technological developments and the needs revealed by the industrial world. This approach needs to have several contracts and conventions to financially support the platforms and the functioning of the network.

A five-year contract with the French Ministry of Higher Education and Research provides core funding for the operating expenses of the GIP structure, and multi-year projects are obtained via the GIP but also via academic institutions in order to update platform equipment (*cf.* sources of funding).

The ultimate aim is to increase the number of players in the field, in line with the shortage of jobs, to meet the challenges mentioned above. Indeed, the number of specialists in the microelectronics field is insufficient. Following an international assessment, the microelectronics industry showed signs of shortage in the subfields considered to be the most important, such as analog electronics, high-frequency electronics, and power electronics, [12]. Based on this analysis, the topics of the network's practical activities are therefore in line with the priorities of the field. The network's centers cover key topics such as computer-aided design of synchronous and asynchronous circuits, embedded electronics, elementary device technologies (VLSI and thin-film technologies), physical and electrical characterization, device and circuit reliability, hardware cybersecurity, electromagnetic compatibility, high-frequency or power components and circuits, and packaging. All these points can be consulted on the GIP-CNFM website.

Every year, some 6,000 users obtain a degree (bachelor's, master's, doctorate) in specialties thanks to know-how. This figure may seem high, but it remains insufficient in the context of the France 2030 plan, which has declared microelectronics to be a national priority for the evolution of the digital domain and AI. Over the next

6 years, the number of graduates in France is set to double!

V. CONCLUSION

The field of microelectronics lays a major role and presents challenges for the future of computing techniques, digital approaches, and artificial intelligence. As these fields are directly dependent on the associated hardware, the challenges are technical, to significantly reduce the electrical energy consumption of all equipment, and human, to cope with the shortage of skills and know-how. Without significant progress in this area, we're heading for a digital dead end. Close cooperation between the two communities seems very important for the future of the planet.

ACKNOWLEDGMENT

The author wants to thank all the members of the French GIP-CNFM network for their discussions and advices. A special thanks to L. Chagoya-Garzon, secretary of GIP-CNFM, for her fruitful advice for the proofreading of this paper.

REFERENCES

[1] G. Kamiya, P. Betoldi, *"Energy consumption in data centres and broadband communication networks in the EU*, Publications Office of the European Union, Luxembourg, 2024, doi: 10.2760/706491.

[2] O. Bonnaud and L. Fesquet, *Microelectronics at the heart of the digital society: technological and training challenges*, 34th Symposium on Microelectronics Technology and Devices (SBMicro), Sao Paulo, Brazil, 2019, pp. 1-4, http://doi.org/10.1109/SBMicro.2019.8919405.

[3] International Energy agency, Electricity Market Report 2023, Reports Electricity 2026, [Online]. https://www.iea.org/reports/electricity-market-report-2023 (Accessed Date: February 8, 2026).

[4] R. Mitova, R. Ghosh, U. Mhaskar, D. Klikic, *Investigations of 600-V GaN HEMT and GaN Diode for Power Converter Applications*. IEEE Transactions on Power Electronics, Vol. 29, No 5, 2015, pp. 2441-2452, http://doi.org/10.1109/TPEL.2013.2286639.

[5] G. E. Moore, *Cramming more components onto integrated circuits,* Electronics Magazine, Vol. 38, No. 8, 1965, pp. 114-117, http://doi.org/10.1109/JPROC.1998.658762.

[6] R.R. Tummala and M. Swaminathan, System on Package: Miniaturization of the Entire System, McGraw-Hill Education; 1st edition, May 2009. ISBN: 978-0-07-145906-8.

[7] S.K. Moore, *Future Transistors, Plastic Processors, and 3D Chips*, IEEE Spectrum Journal, 31 Dec. 2022 ISSN: 00189235, 19399340. https://spectrum.ieee.org/3d-chips-plastic-processors (Accessed Date: February 8, 2026).

[8] A. Auberton-Hervé, *Smart Cut Process Technique—An Overview*, Electronic Design Newsletter, 12 May 2003, [Online]. https://www.electronicdesign.com/technologies/embedded/article/21768797/smart-cut-process-techniquean-overview (Accessed Date: February 8, 2026).

[9] R. Sithanandam, M. Kumar, *A New On-Chip ESD Strategy Using TFETs-TCAD Based Device and Network Simulations*; IEEE J. of EDS, Vol. 6, 2018, pp. 298-308. http://doi.org/10.1109/JEDS.2018.2797054.

[10] J.-R. Lèquepeys, M. Duranton, S. Bonnetier, S. Catrou, R. Fournel, *Overcoming the Data Deluge Challenges with Greener Electronics*, Proc. of ESSDERC-ESSIRC'2021, 2021, pp. 7-14, http://doi.org/10.1109/ESSDERC53440.2021.9631774.

[11] *(text in French)* CNFM, "Coordination Nationale pour la formation en Microélectronique et nanotechnologies", *(National Coordination for Higher Education in Microelectronics and Nanotechnologies), GIP-CNFM*, [Online]. https://cime.grenoble-inp.fr/fr/reseau-cnfm (Accessed Date: February 8, 2026).

[12] D. Manners, EU Skills Shortage, Electronic Weekly, [Online]. https://www.electronicsweekly.com/blogs/manerisms/dilemmas/eu-skills-shortage-2026-05/ (Accessed Date: February 8, 2026).

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
The main French national projects obtained by the GIP are the national IDEFI project, FINMINA, for Innovative Training in Microelectronics and Nanotechnologies (ANR-11-IDFI-0017), and the France 2030 plan project, INFORISM, for Innovative and Strategic Training Engineering in Microelectronics (ANR-23-CMAS-0024). Each network partner receives further financial support each year in the form of co-financing from companies, regional programs, European programs, and research organizations such as the CNRS.

Conflict of Interest
The authors declare no conflict of interest.