Moving to Green ICT:
From Stand-Alone Power-Aware IC Design to an Integrated Approach to Energy Efficient Design for Heterogeneous Electronic Systems

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***Abstract*—Energy efficiency is one of the most critical aspects of todays information society. The most obvious benefits of being Green are reduced environmental impact and cost savings. Reducing energy consumption of electronic devices, circuits and heterogeneous systems, however, is not trivial. This requires the development of innovative energy-aware vertical design solutions and EDA technologies for next generations' nanoelectronics circuits and systems, and the related energy generation, conversion and management systems.**

I. The Need for Green Electronics

It has been estimated recently that over one third of the total energy consumed yearly is electrical energy; ICT is responsible for about **12%** of such electrical energy consumption. This has dramatic implications also on pollution, global warming and climate changes. In 2007, the energy consumption due to ICT produced an amount of CO_2 equal to **25%** of the total CO_2 produced by all the automobiles world-wide. And if the sector continues growing at the current rate, emissions are expected to increase by another 60% by the year 2020.

In spite of these dramatic figures, there are several margins for improving them. First, there are substantial inefficiencies in the ICT technologies (materials, devices, hardware designs techniques, software) that could be removed. Second, use behaviors can significantly impact the user-dependent nature of energy consumption. While the latter solution can only be addressed by a cultural shift, the former pertain to the industrial and research community. By looking at the typical breakdown of the sources of ICT energy (Figure I, Source: *Gartner*), we can observe that computation (PCs + servers) takes about $2/3$ of all the ICT energy, emphasizing the fact that energy-efficient hardware is the most direct lever to achieve energy reduction. Therefore, electronics at large can play a key role in the complete electrical energy supply chain.

Nevertheless, there exists a huge number of electronic products which are characterized by heterogeneous integration of digital, analog and power devices. In these cases, power is consumed not only in the electronic devices and circuits, but also in the electrical appliances and complex systems (e.g., aircrafts, vehicles) in which the electronics plays a fundamental role in energy conversion, management, storage and distribution, thus it may contribute to substantially reduce the demand of electricity needed by the appliances to work.

It is clear that *Green* ICT can only be achieved if the new generations of nanoelectronics devices, circuits and systems belonging to any application domain (ICT, automotive, transportation and renewable energy) are conceived, designed and manufactured with energy efficiency as primary target.

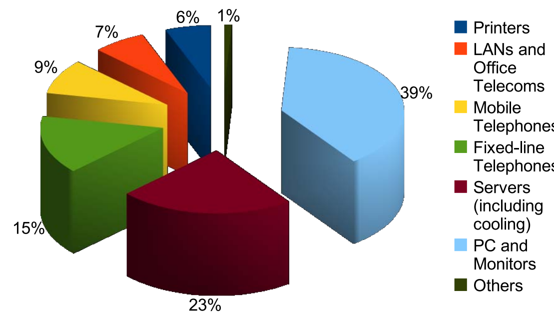

Fig. 1. Sources of Energy Consumption.

II. Understanding Energy Consumption

In recent years, power consumption in CMOS Integrated Circuits (ICs) has steadily increased with each technology generation, due to a combined effect of non-decreasing die size, increased interconnect-related dynamic power and device static (leakage) power. According to Moore's Law, in fact, logic density increases, approximately, by 5X every five years, while transistor density for FLASH memories increases, approximately, by 10X every five years. Such a fast technology scaling results in an increase of power consumption (both dynamic and static) by 2X every five years [3]. For this reason, the reduction of the power consumed by CMOS ICs, implementing both digital and analog/RF functions, has been the common theme of the vast majority of the R&D activities of both universities and industries of the last decade.

However, while power consumption analysis and optimization of digital CMOS devices remain a serious concern, many other issues are becoming a major concern. For instance, it is true that digital design is definitely important, but complex systems-on-chip design starts rapidly decreasing in number - due to complexity and cost factors. Moreover, many European companies are market leaders in electronic products, which do not require top-of-line billion-transistor SoC architectures, but are characterized by heterogeneous integration of digital, analog and power devices. In these products the power consumed by digital logic is often a minor concern, while the energy-

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Electricity Consumption			Saving Potential	KEY Technology
Consumer power supply - stand-by - active mode, ...	Others 18%	stand-by active	>90% >>1%	CoolMOS™, SiC Snart control ICs, CoolSET™
Computing power supply - stand-by, active mode, ...	Information & Comm. 12%	80+/90+	>>1%	CoolMOS™, SiC, Smart control ICs Low cost uC
EC-Ballast Daylight dimming HID, LED, ...	Lighting 15%	Electronic control	>25%	CoolMOS™, Smart ballast ICs Low cost uC
Factory automation Process engineering Heavy industry Light industry, ...	Motors 55%	Variable Speed Drive (VSD)	25% ... > 40%	IGBTs Modules CoolMOS™ Optimized uC 8bit/16bit/32bit
Transportation: Train, bus, car, ...		VSD + Bi-directional		
Home appliance: Fridge, washing machine, Air conditioning, ...		VSD		

Fig. 2. Main Sources of Electrical Energy Consumption.

transfer efficiency of power components and/or the analog subsystems is dominant.

For example, Nokia claims that two-thirds of the electricity used by mobile phones is wasted due to the fact that, when left plugged into the socket, chargers continue to use a small amount of electricity even if the phone is disconnected. Though the power used is generally less than 0.5W, even for the most energy-hungry charger, it is estimated that if the three billion people owning mobile phones today would switch to an energy-efficient, four or five-star charger, this could save the same amount of energy each year as produced by two medium sized power plants.

Figure II reports a quantitative analysis of the main sources of electrical energy consumption. The largest fraction of the electricity is consumed by motors (55%) and lighting (15%). An additional 18% is consumed by various sources, including a large amount of energy wasted due to power supplies that are connected to electrical devices in stand-by mode.

The diagram above shows that all electrical appliances, such as the motors used in factory automation, process engineering, heavy industry, light industry, transportation systems (trains, cars, buses) and home appliances (e.g., refrigerators, washing machines, air conditioners, heaters), as well as most lighting systems, include electronic circuits that are dedicated to control functions, energy conversion, storage and management, and that may contribute to substantially reduce the demand of electricity needed by the appliances to work.

III. Some Hints on How to Get There

Reducing energy consumption of electronic devices, circuits and systems, paired to improving energy generation, conversion, storage and management capabilities represent the biggest challenges that engineers and scientists operating in the electronics sector will have to face in the next decade.

Solid-state devices, integrated circuits and systems based on these devices, have an increasingly pivotal role in all steps of the energy production and management pipeline. Advances in electronics have made it possible to increase the $intelligence$ of energy generation, conversion, distribution: We are now entering the era of smart power grids, smart energy consumption metering and monitoring, smart energy conversion [1]. In these contexts, the term $smart$ implies awareness of environmental conditions, coupled with the capability of suitably adapting system behavior without direct and continuous human intervention. For instance, photovoltaic (*PV*) energy conversion can greatly benefit from adaptation to solar irradiation of the panel operating points, to maintain maximum power transfer from the PV panels to the electric plants under a wide variety of environmental conditions. Clearly, the cost of intelligence must be much lower than the advantages it brings in terms of increased efficiency, responsiveness, robustness. This implies non-trivial design choices and trade-offs, which can be explored only with adequate design automation support. For instance, maximum power point tracking (MPPT) solutions are justified only when they produce an increase in the energy collected by a PV panel significantly greater than the energy they consume to monitor solar irradiation and to compute optimal panel operating point [2]. Quantitatively determining if an MPPT solution has a positive energy balance requires accurate modeling not only of the PV panel itself, but also of the energy conversion circuits and the mixed-signal circuits that monitor power transfer and compute the optimal panel operating point [4]. Robust and accurate modeling, in fact, is only a facet of the problem: Computer-aided design exploration/optimization is another, equally-important aspect, as the complexity of design solutions is such that manual exploration would be too slow, error-prone and expensive.

It is clear, that the achievement of the $Green\ Dream$ will require innovative holistic approaches.

Distinguishing feature of this new R&D approach is that it unifies, under a common design platform, the development of modeling, simulation, design and EDA techniques for devices and systems of different nature and purpose (digital blocks, analog/RF blocks, discrete components), as well as the conception and experimentation of new power supply systems, with particular emphasis on energy management aspects. This enables a synergic approach to energy-aware design, thus offering a comprehensive set of solutions covering the many different facets of the complex problem of accounting for energy effects during the design of heterogeneous circuits and systems, such as those that will be hosted by the electronic products of the future.

This new design paradigm will make possible the introduction of innovative solutions in many different application domains, like: $1)$ Renewable energy generation and management, $2)$ networking and high performance mainframes, $3)$ safety-critical applications in which energy-efficiency is evaluated as a proxy metric for reliability, $4)$ ultra-low-power multi-supply (photovoltaic, vibration, RF-transmitted, and temperature gradient-based) smart wireless sensor networks.

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