CATRENE Scientific Committee

Executive Summary: Energy Autonomous Systems: Future Trends in Devices, Technology, and Systems

Background

Electronic devices have brought exceptional computational power in an ever-shrinking system footprint. This trend has enabled amongst others the wealth of nomadic battery powered wireless systems that society currently enjoys. Emerging integration technologies enabling ever-smaller volumes and the associated increased functional density may bring about a new revolution in systems targeting wearable healthcare, wellness, lifestyle and industrial monitoring applications.

Even though low-cost batteries have been fostering the expansion towards nomadic systems, they currently delay a further expansion as battery replacement or disposal is not an option in many of the envisaged applications and energy density is insufficient to achieve adequate autonomy.

To overcome this bottleneck, another energy paradigm is needed and energy harvesting from the environment may provide a solution. A decade of research in the field of energy harvesting has led to the efficient capturing of small amounts of energy from the environment that can be transformed into electrical energy. In parallel, suitable power management techniques are increasing the available energy budget, e.g. by dynamic optimization of voltage and clock rate, hybrid analog-digital designs, and clever wake-up procedures. Furthermore, advances in microprocessor technology have dramatically increased power efficiency, effectively reducing power consumption requirements. Together these developments have stirred the interest in new applications that rely entirely on energy harvesting for system power.

Objectives and Procedure

In 2008 the CATRENE Scientific Committee established a Working Group on Energy Autonomous Systems (EAS) with the mission of writing a White Paper on this topic. The approach was to gather European experts from academia and industry representing various areas related to EAS in order to: i) define the field, ii) review the current state-of-the-art, iii) discuss the future impact of EAS technologies on the electronics industry and on society at large, iv) identify Europe's strengths and weaknesses, and v) formulate recommendations with respect to public initiatives, efficient research and education. Special care was devoted to the boundaries within this multidisciplinary scientific field. One of the main outputs of this study has been the preparation of a Technology Readiness Levels (TRLs) document for each of the areas of the report: energy harvesting and sources, ultra low-power systems and power management. These TRLs make a forecast of existing technologies by assessing the present state of development as well as a projected timeline for future developments in the next 5 and 10 years, respectively. The EAS working group organized six meetings in the course of 2008 and presented a final version of the report during a open workshop organized at the CATRENE Office in Paris on December 1st 2008. Constant support and follow-up was provided by the CATRENE Scientific Committee.

Definitions and Applications

EAS are electronic systems that have been designed to operate and/or communicate as long as possible in complex environments providing, manipulating and storing information without being connected to a power grid. These systems are intended to operate in out-door or industrial environments as well as in medical in-vivo applications in the diagnostics and therapeutics areas. The targeted power levels should be significant (hundreds of $\mu W/cm^3$) and it is likely that several generations of prototypes will be necessary to achieve the goal of a system totally independent from the energy point of view. Table I compares the available energy and sustainable power of various artificial and environmental sources.

Regarding the current status-of-the-art we will refer to systems with the ability to operate with less than one hundred of µW of power within less than some cm^3. Examples of such systems are nomadic devices operating at ultra low power (wireless sensor networks, in-vivo sensors and actuators, ambient intelligence devices, "smart dust"). *Energy Autonomous Systems* are considered roughly divided in three categories. The first is *Energy Generation*, that consists of *Energy Harvesting* referring to any device or system that can harvest energy from correlated or uncorrelated sources of energy and *Energy Sources* which include any kind of energy storage element used to accumulate excess energy. The second is *Energy Conversion and Optimization* that involves any energy conversion within the system and finally *Energy Consumption* that is related to data acquisition, storage and transmission.

Power Source	Power Density ($\mu W/cm^3$)	Energy Density (J/cm^3)	Energy Density ($\mu W \cdot yr/cm^3$)
Primary Battery	-	2880	90
Secondary Battery	-	1080	34
Micro-fuel Cell	-	3500	110
Ultra-capacitor	-	50-100	1.6-3.2
Heat engine	-	3346	106
Radioactive (^{63}Ni)	0.52	1640*	0.52
Solar (outdoor)	15000	-	-
Solar (indoor)	10	-	-
Temperature (ΔT=10K)	40	-	-
Human Power	330	-	-
Air flow	380	-	-
Pressure Variation	17	-	-
Vibrations	200	-	-

*Reasonable Target: 100$\mu W \cdot yr/cm^3$. *Over 100 years of half-life.*

Table I. Comparison of artificial and environmental power sources from an energy point of view (Shad Roundy, "Energy Scavenging with a Focus on Vibration-to-Electricity Conversion for Low Power Wireless Devices", PhD thesis, University of California, Berkeley, 2003)

Energy Autonomous Systems may contribute to many applications in various sectors. Among them portable autonomous systems could open new endemic scenarios for wireless sensor networks, in situ monitoring for mobile/moving systems, body area networks, biomedical devices, portable power generation for mobile electronics.

Organization of the Report

The report has been organized from the designer perspective on the basis of the EAS functional units mentioned above. It is not a mere classification of various technologies and applications present on the market. This is why this report is different from currently available market reports on the subject. In an introductory section, EAS are defined and classified according to the application constraints and scalability. The next four sections are related to: Energy Harvesting, Energy Sources, Ultra Low Power Systems and Power Management. The first two are related to the *Energy Generation* section whilst the third and the fourth to the *Energy Conversion and Optimization* and *Energy Consumption*, respectively. Each of these sections starts with a "Science and Technology" subsection where the state-of-the-art of the technology is reported and discussed. Then, each section ends with a "Commercial Exploitation" section containing the Technology Readiness Levels mentioned above. In the next section of the report entitled "European Situation and Forward Look" an overview is given of funding opportunities and supporting actions in Europe. Interdisciplinary education and training is also discussed. This section of the report also addresses a set of recommendations which are summarized here.

Recommendations

In order to fully benefit from the opportunities offered by EAS, there is a strong need for public initiatives, new research procedures and interdisciplinary education.

Recommendations on public initiatives (European and national levels)

1) **Put stronger emphasis on EAS initiatives in ongoing programmes so as to transform the results of research activities into commercially exploitable innovation using EC frameworks.**

The purpose is to decrease as much as possible the time needed to transform the results of research activities into commercially exploitable innovation. An example of networks being created are the Knowledge and Innovation Communities Initiatives. EC initiatives should also be the framework where the academic and industrial communities meet in a highly synergetic way.

2) **Increase the opportunities for EAS themes in FP7 outside the ICT arena (i.e. consider also Health, Nanotechnology, Food & Agriculture, Transport) by giving a clear identity of those topics in related calls.**

The purpose is to stimulate the diffusion and the acceptance of EAS technologies by being less discriminatory with respect to the domains of applications. Furthermore, EAS themes in FP7 have frequently been embedded in other calls related to different topics, such as *heterogeneous materials*, *lab-on-a-chip*, *packaging*, etc, where no clear identity of the EAS field of research so far emerged.

Recommendations to couple research and application projects

3) **Have a systemic approach to EAS architectures where the total efficiency plays the most important role and reduce the overlaps on topics related to energy-harvesting principles.**

The purpose is to focus the research on the overall energy chain related to the operating conditions and environment. A function can be highly efficient in a given operational and environmental domain, but be very inefficient in other domains. Only the overall energy efficiency from the environment to the *service* provided is relevant. More emphasis on the development of critical operational functions such as the *dynamic-matching*, *input regulators* and *wake-up* blocks would also be beneficial. Moreover, since energy-aware electronic design plays a pivotal role in the overall performance, it should be included in research project definitions.

4) **Encourage the research on new materials for energy harvesting (i.e. piezo meta-materials, nanotechnology based materials) taking also into account the reliability and durability issues.**

Artificial materials could bring higher conversion efficiencies. New ideas are necessary to address applications where mechanical flexibility, reduced available power and multiple energy sources from the environment have to be dealt with. New material developments are also necessary for micro-energy storage like secondary batteries, capacitors and micro fuel cells. Device reliability is the key to raise the confidence level of the customers, which drives the commercial success.

Recommendations on educational issues (European and national levels)

5) **Promote educational support actions in FP7 on EAS themes by fostering new educational training paths for European graduates and by encouraging introduction of young trainees in public or private laboratories.**

The strategic purpose here is to supply the European Industry and Research Centres with young people with skills and knowledge in more domains than currently available. Making systems operational and effective -- whatever the scale considered -- brings together multiple domains of science. On the other hand, innovations very often come from mixing ideas from different domains. However, science and technology education is still not addressing multiple expertise domains.