ZEROPOWER Strategic Research Agenda

Executive Summary

The promise of a novel, smarter society, where ubiquitous, mobile, interconnected, always-on, electronic devices provide sensing and actuating capabilities to distributed control systems, will not be realized until the powering issue is solved. In order to reach such a goal, the scientific and technological community need to bridge the existing gap between how much energy is required for operating the devices and how much energy is available at the device location.

The ZEROPOWER research agenda is about the activities that the science and technology related actors need to undertake in order to fill this gap. On one side it is required that the amount of energy presently dissipated by ICT devices during their operation is decreased down to the lowest limits compatible with the basic physics laws. On the other side it is required that technologies associated with ambient energy harvesting are improved to maximize the energy conversion efficiency up to the their thermodynamic limits.

Benefits from the development of this research agenda will be paramount.

The development of new self-powered, energy-harvesting technologies that would enable micro- and nano-scale sensors and actuators will deeply affect the way we think and operate our societies. As examples, ZEROPOWER autonomous sensors for temperature and pollution monitoring are key for SMART metering to reduce energy consumption in domestic and industrial environments. ZEROPOWER autonomous sensors for healthcare applications have the potential to change the expensive reactive healthcare market to a cheaper and more effective point-of-care diagnostic system. Such healthcare sensors also have the potential to radically change the care of the elderly to a more sustainable and scalable automated monitoring rather than present expensive labour intensive methods.

Societies reliance and use of Information Communications Technology (ICT) is increasing with 2% of all energy consumption now the result of ICT use. This is supposed to reach 5% by 2020. FP7-ICT has highlighted ICT as a key engine of growth, with the use of ICT to improve energy efficiency by managing energy demand and use. The energy consumption and carbon dioxide emission from the expanding ICT use, however, is unsustainable and will impact heavily on future climate change. Methods are required to make ICT technology more energy efficient.

Such technologies provide an opportunity for Europe to lead and generate significant economic benefit whilst simultaneously addressing climate change, healthcare and manufacturing efficiency benefits. Developing ZEROPOWER technology will be key for Europe to meet many of the Europe 2020 targets.

To achieve such goals, Europe needs to invest in research and development programmes to be first to deliver these technologies to market. The potential market for energy harvesters for ICT alone is predicted to be €5.7 Bn by 2021 whilst autonomous sensors in healthcare have the potential to save up to €271 Bn per annum through improved delivery of healthcare services. Therefore the potential for positive return on investment for developing ZEROPOWER technology is enormous.

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I Introduction and Background

The ZEROPOWER strategic research agenda is a document that summarizes the attempt of the scientific and technical community gathered around the ZEROPOWER initiative[1], to provide a reference for the activities required in order to fill the gap between how much energy is required for operating autonomous ICT devices and how much energy is available at the device location.

Depending on the application framework this gap ranges in power between[2] 1 μW and 1 mW.

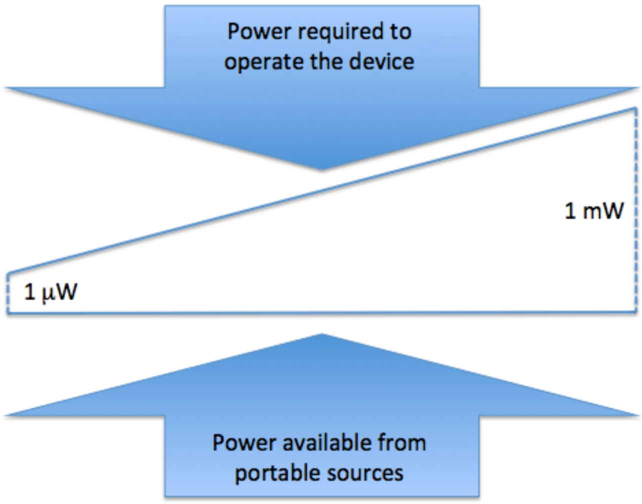

Figure 1. The gap between how much energy is required for operating autonomous ICT devices and how much energy is available at the device location. This gap ranges in power between 1 μW and 1 mW.

In order to bridge such a gap actions need to be undertaken on both sides of the gap. On one side it is required that the amount of energy presently dissipated by ICT devices during their operation is decreased down to the lowest limits compatible with the basic physics laws. On the other side it is required that technologies associated with ambient energy harvesting are improved to maximize the energy conversion efficiency up to the thermodynamic limits. In this document we mainly focus on the latter aspect while not forgetting the former.

Benefits from the development of this activity will be relevant in two respects:

1) The growth of energy efficiency with the consequent energy saving

2) The enabling of a new class of micro and nano sensors and actuators

[1] ZEROPOWER is a co-ordinated activity among the consortia involved in the EC Future Emerging Technology (FET) Proactive Initiative "Towards Zero-Power ICT" research projects (FET proactive call FP7-ICT-2009-5, Objective 8.6) and communities of scientists interested in energy harvesting and low power, energy efficient ICT (Information and Communication Technology). This activity is aimed at assessing the impact of the research efforts and proposing measures to increase the visibility of ICT-Energy related initiatives to the scientific community, targeted industries and to the public at large through exchange of information, dedicated networking events and media campaigns. Since its start the ZEROPOWER activities are generating broader acceptance for the developed technology and the benefits of its applications. ZEROPOWER is also facilitating broader interaction and feedback among the "Toward Zero-Power ICT" consortia members and stakeholders, thereby, consolidating progress in the field. Most importantly, from the ZEROPOWER activity, positive benefits to the European Community are foreseen in all great challenges of energy, security, environment and health.

[2] ICT-Energy, InTech, 2014.

I.1 Energy Efficient ICT

ICT has become a strategic sector in the world economy. Its impact on cultural and social development is already paramount and it will keep growing in the foreseeable future. State of the art ICT is presently based on digital devices whose functioning is currently dominated by power dissipated in heat. This is a major problem for a number of reasons.

1. *Economic and social reasons*. Energy efficiency in operating ICT devices is presently considered an objective of extremely high economic relevance. According to the SMART 2020[3] study, "the share of ICT on the worldwide energy consumption today is in the range of 2-5%. Given that the use of ICT will further increase and the overall energy consumption will hopefully decrease due to the help of ICT and other measures, it is expected that the share of ICT on the worldwide energy consumption will grow in the future. Carbon dioxide emissions from the use of ICT are therefore presently increasing. Hence, it becomes more and more important to consider and improve the energy efficiency of ICT. On the short term, it will be an obvious and practical solution to better exploit the potential of technologies that already exist or are currently in the making. On the long term, new and disruptive ideas will be needed"[4].

2. *Technological reasons*. In the last forty years the semiconductor industry has been driven by its ability to scale down the size of the CMOS Field Effect Transistor switches, the building block of present computing devices, and to increase computing capability density up to a point where the power dissipated in heat during computation has become a serious limitation. According to the International Technology Roadmap of Semiconductors[5] the limits imposed by the physics of switch operation will be the roadblock for future scaling in the next 10-15 years. The limit on the minimum energy per switching is set at approximately 3 $k_B T$ ln(2) (approx 10^{-20} J at room temperature)[6]. Power dissipated versus switching speed of devices have been characterized since the 1970s[7] by a linear scaling rule where micro-fabrication capabilities, through the replacement of bipolar transistors with CMOS, allowed the continuation of the exponential increase trend in information processing capability which has been known as Moore's law. However, since 2004 the Nanoelectronics Research Initiative[8], a US based consortium of Semiconductor Industry Association companies, has launched a grand challenge to address the fundamental limits of the physics of switches. Such limits are mainly represented by the minimum energy and minimum time, required to operate a switch. With the present estimate of the minimum energy required in current CMOS technology (with the Field Effect Transistor channel scaled down to 1.5 nm, switching speed of about 40 fs) the resulting power density for these switches at maximum packing density would be on the order of 1 MW/cm^2. This is orders of magnitude larger that what is presently

[3] "SMART 2020: enabling the low carbon economy in the information age" is a report published by "The Climate Group", an independent, not-for-profit organization. The report is available here: http://www.theclimategroup.org/_assets/files/Smart2020Report.pdf

[4] *Disruptive Solutions for Energy Efficient ICT*, Expert consultation, FET Proactive, 2010. Available at: http://cordis.europa.eu/fp7/ict/fet-proactive/docs/shapefetip-wp2011-12-10_en.pdf

[5] ITRS (International Technology Roadmap for Semiconductors), Semiconductor Industry Association, 2001, http://public.itrs.net.

[6] R. K. Cavin, V.V. Zhirnov, D. J. C. Herr, A. Avila, and J. Hutchby, Research directions and challenges in nanoelectronics, J. Nanoparticle Res., vol. 8, pp. 841–858, 2006.

[7] G. Baccarani, M. R. Wordeman and R. H. Dennard, IEEE Trans Electron Devices, 31(4), 452–62, 1984.

[8] The Nanoelectronics Research Initiative (nri.src.org) was formed in 2004 as a consortium of Semiconductor Industry Association (SIA) (www.siaonline.org) companies to manage a university-based research program as part of the Semiconductor Research Corporation (SRC) (www.src.org).

technologically manageable, thus the amount of energy dissipated through heat is presently the major roadblock for continuing the increase in computing performances.

3. *Scientific reasons*. Presently the main effort to overcome the technological limitations is aimed at cooling down the heat produced during computation with specific attention to the charge transport on one hand and on the other hand on reducing the voltage operating levels up to the point of not compromising the error rate due to voltage fluctuations. Such a strategy has produced some interesting results[9] however it is clearly coming soon to an end due to the unsustainable energy input requirement. There are attempts to look at the problem from a more fundamental point of view by addressing the basic mechanisms behind the heat production and the role of fluctuations arising by lowering the threshold voltages.

I.2 Micro- and Nano-scale Wireless Sensors and actuators

MEMS (Micro Electro-Mechanical Systems) and NEMS (Nano Electro-Mechanical Systems) technology has made significant progress in the last ten years and a new potential in distributed sensing and actuating devices is now approaching the market. There is an increasing demand for ambient intelligence devices, various kinds of sensor networks for safety and environmental monitoring and for monitoring of the health of humans and animals.

In the last few years Wireless Sensor Networks (WSN) have attracted a lot of interest both in academia and industry. Nowadays, thanks to advances in MEMS technologies, it is feasible to fabricate cheap and small sensor nodes that have not only sensing, but also data processing and communicating capabilities. WSNs differ from traditional wireless network by features like the number of nodes, constrains on energy consumption, computation and memory. Obviously these unique characteristics bring new challenges to the research activity. One of the advantages of wireless communication is the easiness in deploying the sensors without the need of wiring and fixed positioning, thus reducing installation and maintenance cost. Furthermore, in some hostile environment it is difficult or even impossible to physically connect the sensors, therefore wireless communication is the only feasible solution. Due to the heterogeneity of potential application for WSN specific objective and constrains have to be taken into account.

These devices all need distributed powering systems. Presently this means wired power-grids, batteries or RF-sources, however all these solutions present some drawbacks. Wiring is expensive, adds weight and is subject to high failure rates in devices subjected to repeated motion. Traditional batteries are not a viable solution to the powering of such devices mainly because they have to be replaced once exhausted and the cost of replacing the batteries is many orders of magnitude greater than the complete cost of the systems. Alternative solutions based on micro fuel cells and micro turbine generators are also not suitable: both involve the use of chemical energy and require refuelling when their supplies are exhausted. Thus the goal of powering such devices with energy harvested from the ambient has been in recent years the subject of a great research effort.

If one can realize an energy harvester with a capacity to deliver power of 1 μW, it would open up a large number of applications. Also, the availability of this kind of power sources would boost the development of even lower power devices, leading to the vastness of autonomous nanoscale ICT systems for implants and in-vivo health monitoring, environmental warning and hazard preventing networks and for other safety measures. In a wider context, electronic devices currently account for 15% of household electricity consumption, but their share is rising rapidly, mainly due to growing demand in Africa and the developing world. Next to the need for more secure and greener energy supplies at a large scale, immediate action has to be taken to employ alternative energy sources and reduce power consumption in consumer electronics at all levels.

[9] See e.g. the Aquasar computer installed on 2010 at the Swiss Federal Institute of Technology (ETH) Zurich.

I.3 Matching Problems with Solutions

Improving energy efficiency in ICT and powering networks of small wireless sensors are two important fields of active research that sit on a common scientific background: the management of energy at the micro- and nano-scales.

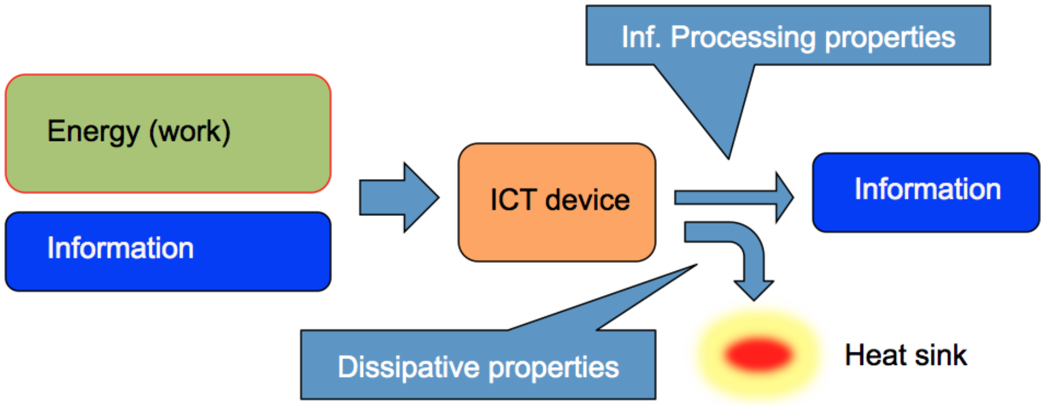

Figure 2. An ICT device is a machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

Relevant scientific breakthroughs are needed on this topic if we want to make progress on the two fields. Specifically, a new approach is required to the energy management physical mechanisms at the nano-scale with the aim of setting the bases for a new thermodynamics of ICT devices. In this perspective an ICT device has to be considered as a machine that inputs information and energy (under the form of work), processes information and outputs information and energy (mostly under the form of heat). Energy efficiency is usually defined as "the percentage of energy input to a device that is consumed in useful work and not wasted as useless heat". This definition, however, does not apply when we deal with processes at nano-scale. Moreover the very basic mechanism behind energy dissipation requires a new definition when non-equilibrium processes involving only a few degrees of freedom are considered: the dream of highly efficient devices has to deal with a rethinking of both energy and information dissipation processes.

The long-term aim of the research activities addressed here is to make possible low power ICT devices with a significant impact on energy efficiency on a much broader scale. Clearly, a new generation of energy efficient ICT device has to deal with energy transformation processes at nanoscale. This is undoubtedly a multidisciplinary task where competences from fields as diverse as physics, computer science, electronic engineering and mechanical engineering are brought together in a coordinated effort.

II Attaining the ZEROPOWER objective

This document has the aim of providing a brief summary of the important reasons for Europe to invest in ZEROPOWER technology. It does not provide the detailed technical calculations for which the reader is directed to a number of roadmaps which provide the technical detail required to deliver ZEROPOWER technology and also the demonstration that ZEROPOWER technology is appropriate for the proposed applications. Nevertheless few key steps to attain a more effective impact of the ZEROPOWER approach are listed here.

II.1 Relevant key steps

In order to more easily attain the ZEROPOWER objective, specific attention should be focused on the following key aspects:

- While energy harvesting technologies for powering *10 cm size* objects have been fully developed and commercial applications and products have already reached the markets, in the micro-to-nano scale domain the activity is still in the research phase. It is important to invest resources and efforts for taking the few relevant studies in the field to a level where prototypes start to appear. The power performance has to target over 1μW per cubic millimeter power density.

- Over the last 10 years the reduction in sensor and microprocessor power consumption leaves wireless data transmission as the most critical area for improvement, although the continuing reduction in power used by sensors and microprocessors will help. More specifically, devices must reliably store enough energy for the duty cycle (and to remain connected or re-join in the case of mesh networks), achieve long lifetimes and possess sufficient energy density. On board, short-time energy storage is a critical issue in this field. Efforts should be devoted to addressing this problem.

- A related issue is the power converter issue, which is technology dependent. For heat source, the converter needs to be able to condition as low a voltage as possible and current-source rather than voltage-source gate driver would make more sense. Research in this area should be enhanced.

- Concerning the physical origin of the ambient energy an approach should be promoted that addresses multiple sources like photovoltaic and vibrations or thermal and vibrations, at the same time. Specific attention should also be given to integrating hybrid harvesters on the same device. Heat dissipation is a very common side effect of operating appliances and man made machines, thus thermal harvesting should be of primary importance.

II.2 Relationship to other Roadmaps

ZEROPOWER objectives can be found relevant in a number of related technological roadmaps. Among these we list:

Energy Harvesting and Storage for Electronic Devices 2011-2012 – IDTechEx (http://www.idtechex.com/research/reports/energy-harvesting-and-storage-for-electronic-devices-2011-2021-000270.asp)

Energy Harvesting for Structural Monitoring – A Roadmap to New Research Challenges, UK EPSRC EH Network Workshop Report, May 2011 (http://eh-network.org/resource1.php)

Energy Harvesting from Human Power – A Roadmap to New Research Challenges, UK EPSRC EH Network Workshop Report, March 2011 (http://eh-network.org/resource1.php)

Power Management Technologies to Enable Remote and Wireless Sensing, UK ESP KTN Report, May 2010 (http://eh-network.org/resource1.php)

Energy Harvesting Technologies to enable Wireless and Remote Sensing, UK Sensors and Instrumentation KTN Report, June 2008, (http://eh-network.org/resource1.php)

III Potential Impact, Applications and Markets

Potential impact from the development of this research agenda will be very significant in more than one aspect. In the following we briefly discuss direct and indirect impact on energy savings and potential applications in the health sector to mention two of the most visible potential results of the research in this area.

III.1 Direct impact on the use of energy

The impact of realising low-power electronics in the energy budget is huge. As global energy demand increases, ICT and consumer electronics (CE) account for one of the fastest growing sectors regarding energy consumption. The International Energy Agency (IEA) projects that by 2030 the global energy use by just residential electronic gadgets could rise to 1,700TWh. This is around 40% of the generation capacity of the largest electricity producer in the world (USA). In fact, it would require at least a dozen of power plants with 1-2GW output to accommodate this trend which if placed in a single location would make that country the third largest electricity producer. In the developed world, roughly one third of the annual electricity bill from residential ICT and CE is charged to computers, peripherals and other mobile devices; audio-visual equipment accounts for the other two third (estimates based on IEA data and an independent study by the Consumers Electronics Association-USA).

III.2 Indirect impact through the introduction of new applications

Even greater benefits may derive from new applications. The Smart 2020 study indicates that "ICT's largest influence will be by enabling energy efficiencies in other sectors, an opportunity that could deliver carbon savings five times larger than the total emissions from the entire ICT sector in 2020." Indeed, miniaturised electronic systems applied in ambient intelligence, point-of-care diagnostics, chemical warfare security, logistics and supply-chain control can potentially achieve large cost/energy savings with additional huge societal impact.

III.3 Applications in the health sector

The OECD Health Data show that an average of 8.9 % of GDP in developed countries is spent on healthcare costs. Over the last 50 years, healthcare spend has outpaced GDP growth by about 2 percentage points a year in most OECD countries and there are few signs that this trend will slow. Advances in e-Health, the healthcare practices supported by ICT, are a very promising route to reduce the bill. For example, point-of-care devices to diagnose Acute Coronary Syndrome can yield results around 1.0 to 1.5 hrs earlier than analysis in the central laboratory, allowing for earlier intervention or rule out to a step down unit. At a cost of €1,300-€6,500 per hour of emergency department bedtime, the shorter turnaround time provides major savings. In particular, m-Health which utilises mobile electronics and communication technologies delivers solutions in prescription drugs monitoring and in remote diagnosis and even treatment for patients who do not have easy access to a physician. Based on ubiquitous intelligence from energy-efficient miniaturised sensors (e.g., in wearable/textile integration), remote health monitoring devices that track and report patients' conditions are possible. Such ICT solutions are urgently needed taking into account Europe's aging population, the even more demanding constraints on resources and patient empowerment. Current estimates on cost savings from m-Health for chronic diseases in OECD countries are valued at €227 - 273 billion. M-Health is already around €2 billion market according to CSMG, and it is expected to grow over the next five years at a 25 percent CAGR (compound annual growth rate). A McKinsey&Company report estimates an untapped consumer-led market potential of up to several tens of billions Euros.

III.4 Market for Wireless Sensor Networks

Estimates of the current WSN market, which is expected to grow rapidly, are at €1-2 billions. The market of energy harvesting ICT devices alone is estimated close to €1 billion in 2011, to grow to around €5.7 by 2021. This is based on "250 million sensors powered by an energy harvester (at an average price of $6 per harvester), and by then numerous consumer electronic devices including laptops, ebooks and cell phones" (IDTechEx Report). However, market fragmentation owing both to enabling technology and end-user application makes it very difficult to reveal the full potential of the market. The healthcare sector was mentioned above. Another short-term windfall impact is expected from application in energy efficient buildings. For example, just the wireless-enabled HVAC sensors (heating, ventilation and air-conditioning) tapped into the building automation systems will size a market of €150 million and will result in multi-billion euro savings (estimates of 40%-50% energy savings have been reported).

The potential benefits from the research and development of low-power nanoelectronic components and autonomous sensors stretch out to many other research areas. Detailed knowledge of the dynamics of energy/information carriers and the realisation of appropriate channels is of paramount importance for Beyond Moore technologies. In the short-to-medium term, the required advances in energy management concepts, ranging from managing dissipation and fabricating thermodynamically efficient devices at the nanoscale to designing materials and circuits for more efficient electronics, will have diverse impact in metrology, nanofabrication, characterisation and modelling, materials research and smart grid applications.

IV Standards and Metrology

To enable comparison of different technologies, a key area that requires development is metrology for energy harvesting systems especially at the micro- and nano-scale. At present there are a lot of bold claims of energy harvesting devices that will save the planet and produce amounts of energy that defy the laws of physics. If consumers and markets are to have the belief and confidence in energy harvesting technologies to allow them to be implemented and used then standards and measurements that allow accurate comparison and benchmarking of the technologies are required. The issues for metrology are that the input sources of energy come from a large range of sources. The energy to be harvested can be in the form of kinetic, potential, electromagnetic, thermal or chemical energy and for ICT will be converted into electrical energy. For each application, different load impedance is likely and the electrical energy needs to be converted and impedance matched to the load. Standards are therefore required for a range of different potential applications to highlight the different areas of energy harvesting. As an example, the efficiency of thermoelectric devices requires the accurate measurements of electrical conductivity and thermal conductivity. Thermal conductivity is already extremely difficult to measure in bulk systems with uncertainties of around 50% due to the difficulty of heat transport through any object that touches the item to be measured. As thermometers are required to measure the temperature, the act of measurement adds uncertainty to the measurement through the parasitic loss of heat. At the micro- and nano-scales, the measurement is far more complicated and difficult and new techniques and ideas are required. For vibrational energy harvesting the issues will be related to what frequency and bandwidth should be used to compare devices.

There is already a European Metrology Research Programme on energy harvesting technologies (http://www.emrp-metrology-for-energy-harvesting.blogspot.com/). The ZEROPOWER network has already discussed a number of collaborative projects on energy harvesting standards and it is clear for future energy harvesting that metrology and standards are at the core of providing robust and quantitative performance data for energy harvesting technologies.

In general, it would be beneficial for the ZEROPOWER community and the society at large to promote proactive actions aimed at forming working groups (with links to NIST, IEEE, IFAC, …) whose goals are to work on a standardization process for performance definitions and related measurement procedures.

V Potential Ethical and Societal Issues

Here we list potential applications of the ZEROPOWER technology with major ethical and societal issues.

V.1 Energy-ICT and carbon emission

A first general issue, inherent to the ZEROPOWER concept, which will have a clear ethical and societal impact is related to the contribution of the ICT to climate change. It is nowadays well established that around 2% of the global emissions of carbon dioxide are due to the manufacture, use and disposal of ICT devices and systems. This percentage can increase to 3% in 2020 if the efficiency of ICT is not improved. ZEROPOWER technologies, including here the binomial **ultralow power electronics – energy harvesting strategies**, will have a double impact in this issue: from one hand they can stop the growth and even reduce the 2% contribution to CO_2 emissions, but on the other hand, they can help to enable the reduction of the remaining 98% of the total emissions produced by non-ICT actors.

V.2 ZEROPOWER and the smart environments

The main way that ICT will be used in improving energy efficiency is through adding smartness or intelligence to the functionalities/systems in which energy efficiency is required to be improved. Thus, new concepts such as **smart city**, **smart work**, **smart grid, intelligent transport** or smart/intelligent whatever will arise that require autonomous sensing systems that consume ZEROPOWER. Zeropower technologies will have the opportunity to demonstrate their capabilities to provide smartness/intelligence to all these functionalities/systems in an energy efficient way.

So, a first type of ZEROPOWER applications will be focused in this so called "ICTs for the energy efficiency improvement of ICT and non-ICT systems". In this class of applications we can include:

-Devices and systems for the improvement of energy distribution, consumption and management in general at home, industries and civil buildings and infrastructures. **Smart grid** concept and extensions of the concept to other kinds of energy as gas or renewables (solar, wind).

-Devices for the energy efficiency improvement of ICT systems and equipment: from tiny integrated microsystems to large data centres.

V.3 ZEROPOWER and the quality of life

A second issue is related to the improvement of society quality of life. Although applications in the previous point have also an incidence to the population quality of life, this incidence is expected to be plausible in a medium-long term. Here, a set of applications which have a short term, more direct incidence to the quality of life are listed:

-Health related applications: Body Area Networks (BAN) technologies for health monitoring of elderly, sick, disabled or newborn people.

-Animal tracking and monitoring: WSN for remote control of position and vital constants of livestock.

-Ambient monitoring: WSN for pollution monitoring in big cities or industrial regions, for fire prevention in forests.

-Geo-atmospheric monitoring: WSN for monitoring, prediction and prevention of natural catastrophes such as flooding, hurricanes, snow slides, earthquakes or tsunamis.

-Security improvement and accident prevention in cars: Systems already implemented in aircrafts that can minimize the probability of collision. Detection of individual or collective behavioural patterns that can lead to a dangerous situation.

-Goods tracking: smart active RFID technologies for the improvement of manufacturing and distribution of goods at the industry and distributor level, but also for helping the user in quotidian buying and consuming activities.

-Circulation improvement of public and private transport in cities. Smart navigation systems for dynamic calculation of efficient itineraries. Smart parking search systems.

-Car navigation systems for improving the efficiency in cities circulation. Parking searching systems in cities.

- The environmental benefit that autonomous device use could produce as a consequence of the significant reduction in wiring requirements. Copper is one of the raw materials critical to the industrial sector and it also has a significant impact on the environment.

- The ubiquitous diffusion of energy autonomous and wireless devices would result in to an enormous reduction of the industrial demand for this increasingly expensive material.

- Moreover, if the automotive or the generic transportation system is considered, the massive reduction of wiring will result in a lower payload that in turn would result in more effective engines, contributing to pollution reduction.

V.4 ZEROPOWER as enabling technology

In general, energy harvesting and ultralow power electronics will act as enabling technologies in all previous applications. Thus, for instance, most of the previous applications are strongly connected to efficient wireless communication technologies and other related technologies such as **wireless sensor networks** (WSN). So, it is well known that WSN technology will not get in real applications, until both energy harvesting and low power electronics will give good solutions for self-powering WSN nodes and for decreasing energy consumption of the sensing and communication functions respectively.

V.5 Outreach and Public Engagement

It is important to educate the public about the energy that ICT devices consume, the carbon dioxide that is produced from the use of ICT devices, how to reduce the energy and carbon dioxide emission from the use of ICT as well as in new technologies that can help reduce both the energy consumption and carbon dioxide emission. Energy harvesting is a developing research area and if it is to be taken up by society, it is important to educate society about the new technology.

ZEROPOWER has already started a large number of public outreach events and any future energy harvesting work must continue this important area to educate society about the benefits of ZEROPOWER technologies, the importance of saving energy and also to encourage the next generation of young scientists and engineers that are need to help build a better European society. Please visit the ZEROPOWER web site (www.zero-power.eu) and join our Facebook group: zeropower.

VI Present Investment in Energy Harvesting

This section will present data on energy harvesting industry and projects funded around the world and known to the ZEROPOWER partners. As this is a rapidly expanding field, it is extremely difficult to cover all companies and government research programmes that are presently underway.

VI.1 European Industry

- EnOcean – German manufacturer of vibrational energy harvesting sources – http://www.enocean.com/
- European Thermodynamics – U.K. manufacturer of thermoelectric energy harvesters and Peltier coolers – http://www.europeanthermodynamics.com/
- Micropelt – German manufacturer of microfabricated thermoelectric energy harvesters – http://www.micropelt.com/
- Perpetuum – U.K. manufacturer of vibrational energy harvesters – http://www.perpetuum.com/
- Smart Material GmbH – vibrational energy harvesting manufacturer and piezoelectric material supplier – http://www.smart-material.com/
- Wisepower – Italian manufacturer of autonomous sensors using vibrational energy harvesting for automotive applications – http://www.wisepower.it

VI.2 European Level and EU National Programmes

- ZEROPOWER, Lead: Perugia, Italy, date: 01-01-2011 to 31-12-2013, FP7-ICT-ICT Network Ref: 270005, €626k
- GREEN Silicon – Generate Renewable Energy Efficiently using Nanofabricated Silicon, Lead: UK Univ Glasgow Date 01-08-2010 to 31-07-2013, FP7-ICT-FET Ref: 257750, €2,205,303
- NANOPOWER – Nanoscale energy management for powering ICT devices, Lead: Perugia, Italy, Date 01-08-2010 to 31-07-2013, FP7-ICT-FET Ref: 256959, €3.46M
- SINAPS: Semiconducting Nanowire Platform for Autonomous Sensors, Lead: Tyndall, Ireland, Date 01-08-2010 to 31-07-2013, FP7-ICT-FET Ref: 257856, €3.09M
- Guardian Angels: Guardian Angels for a Smarter Life, Lead: EPFL, Switzerland, Date: 1-5-2011 to 30-4-2012, FP7-ICT-FET Ref: 285406, €1.75M
- GENESI : GENESIs: Green sEnsor NEtworks for Structural monitoring, Lead: Roma, Italy, Date 01-04-2010 to 31-03-2013, FP7-ICT-FET Ref. No.: 257916, €3.01M
- GREENERBUILDINGS : An ubiquitous embedded systems framework for energy-aware buildings using activity and context knowledge, Lead: Technical University Eindhoven, Netherlands, Date: 01-09-2010 to 31-08-2013, FP7-ICT-FET Ref. No. 258888, €2.98M
- NANOFUNCTION : Beyond CMOS Nano-devices for Adding Functionalities to CMOS, Lead: Grenoble, France, Date: 01-09-2010 to 31-08-2013, FP7-ICT-FET Ref. No. 257375, €3.53M
- ROTROT : ROll To Roll production of Organic Tandem cells, Lead: CEA, France, Date: 01-09-2011 to 31-08-2014, FP7-ICT-FET Ref. No. 288565, €4.63M
- SMART-EC : Heterogeneous integration of autonomous smart films based on electrochromic transistors, Lead: Fiat, Italy, Dates: 01-09-2010 to 31-08-2014, FP7-ICT-FET Ref. No. 258203, €7.04M
- TIBUCON : Self Powered Wireless Sensor Network for HVAC System Energy Improvement - Towards Integral Building Connectivity, Lead: Warszawa, Poland, Dates: 01-09-2010 to 31-08-2013, FP7-ICT-FET Ref. No. 260034 €2.64M
- WIBRATE : Wireless, Self-Powered Vibration Monitoring and Control for Complex Industrial Systems, Lead: University Twente, Netherlands, Dates: 01-09-2011 to 31-08-2014, FP7-ICT-FET Ref. No. 289041, €4.31M

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- NANOSINTHER - Sintering technology for Thermoelectrics - DLR 2005 – 2007 Marie Curie
- NEAT - Nanoparticle Embedded in Alloy Thermoelectrics, Country: FRANCE, 01-04-2011 to 31-03-2014 Ref: 263440 Funding total €4006262 FP7-NMP
- Thermal and Thermoelectric Transport in Nanomaterials, Country: FRANCE Date: 11-09-2008
- Spark Plasma Sintering Nanostructured Thermoelectrics, Country: UK Date: 01-08-2011
- Nanostructured Electron Heat Engines, Country: SWITZERLAND Date: 20-10-2010
- NANO-TEC – Nano-engineered high performance Thermoelectric Energy Conversion devices, Country: SPAIN Start date:2010-03-01 End date:2015-02-28, AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS, Project Reference: 240497 Project cost: €1228000 Project Funding: €1228000
- Computational Thermoelectrics, Country: SWEDEN, Date: 23-09-2009
- Design of new thermoelectric devices based on layered and field modulated nanostructures of strongly correlated electron systems Country: SPAIN, Date: 24-01-2011
- Nano-layered thin films of quaternary bismuth telluride lead selenide for low-dimensional thermopile devices ,Country: GERMANY Date: 20-10-2009
- NANOSICON, Nanostructured Silicides, GERMAN AEROSPACE CENTER, Country: GERMANY, Date: 02-08-2011
- High-temperature stable nano-structured silicides for highly efficient thermogenerators and their contacting technology, Country: GERMANY, Date: 31-08-2010
- ThetaGen, Thermoelectric generator for engine control system ,Country: FRANCE, Date: 17-02-2011
- Reduced energy consumption by massive thermoelectric waste heat recovery in light duty trucks , Country: ITALY, Date: 12-05-2010
- Next Generation Nano-engineered Thermoelectric Converters - from concept to industrial validation, Country: SWEDEN, Date: 01-06-2011
- Harnessing Fluctuations: phononics and thermal energy, Spain
- IMS - Integrated modular system for energy self-sufficient buildings based on thin film photovoltaic and thermoelectric devices
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- First-principles engineering of thermal and electrical transport at the nanoscale, Country: UNITED KINGDOM, Date: 23-09-2011
- HEATRECAR - Reduced Energy Consumption by Massive Thermoelectric Waste Heat Recovery in Light Duty Trucks Date: 06-01-2010
- NEXTEC - Next Generation Nano-engineered Thermoelectric Converters - from concept to industrial validation Date: 01-06-2011
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- Towards the analysis of energy conversion materials at the atomic scale, Country: UNITED KINGDOM, Date: 27-09-2010
- Novel oxides with specific magnetic/transport properties, Country: FRANCE, Date: 05-01-2010

- Materials and interfaces for energy conversion and storages, Country: SWEDEN, Date: 15-10-2011
- Enhanced energy production of heat and electricity by a combined solar thermionic-thermoelectric unit system, Country: ITALY Date: 12-10-2011
- UK EPSRC Energy Harvesting Network, Lead: University of Southampton, U.K. Dates: 01-03-2010 to 28-02-2013, UK EPSRC EP/H013458/1, £112,278
- Next Generation Energy-Harvesting Electronics - holistic approach 1763, Lead: University of Southampton, U.K. Dates: 01-10-2009 to 30-09-2012 UK EPSRC EP/G067740/1, £722,136
- Energy Harvesting Materials for Smart Fabrics and Interactive Textiles, Lead: University of Southampton, U.K. Dates: 01-10-2010 to 30-09-2015 UK EPSRC EP/G067740/1, £910,196
- Sandpit: Mobile Energy Harvesting Systems, Lead: University of Leeds, U.K., Dates: 25-10-2009 to 24-10-2011, UK EPSRC EP/H020764/1, £877,929
- "Innovative microsystems based on nonlinear dynamics for improved energy harvesting from ambient vibrations"; lead: Catania, Italy; Ministero Istruzione Università Ricerca, bando PRIN 2007.
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VII Competitor Analysis

The US and Asia (particularly Japan) have a number of relatively small programmes in energy harvesting but no country or region is presently dominating the energy harvesting market.

VII.2 In the US

In the US, most of the initial work has been funded by DARPA for military applications but the US Department of Energy has run a number of workshops over the last few years discussing energy harvesting as a future technology. This suggests the US is presently looking at the business case before investing research funds in the field. There is therefore significant potential to invest and deliver significant return on investment if Europe invests in developing ZEROPOWER technology today.

US are pioneer in developing the concept of self-powered sensing and wireless communicated devices. A clear example, the Smart Dust Project leaded by Prof. Kris Pister in UC Berkeley in the 90's, became a company named Dust Networks. Dust Networks products are built on break-through Eterna™ 802.15.4 SoC technology, delivering ultra-low power consumption for wire-free operation on batteries or energy harvesting.

Another industrial project derived from the Smart Dust concept is the "Central Nervous System for the Earth" Project (CeNSE) developed in Hewlett-Packard Labs in Palo Alto. The objective is to deploy a trillion wireless sensors all over the planet in order to see if ecosystems are healthy, detect earthquakes more rapidly, predict traffic patterns and monitor energy use. The idea is that accidents could be prevented and energy could be saved if people knew more about the world in real time, instead of when workers check on these issues only occasionally.

Another focus of Zeropower activity can be found at the Berkeley Wireless Research Center, where Profs. J. Rabaey, P. Wright and E. Alon lead the group of "Energy Efficient Wireless Systems". The group developed the Pico Radio concept, which brought to the limit the power consumption of CMOS based wireless transceivers using ultra-low power design techniques.

Also at Berkeley, Prof. Liwei Lin Laboratory has an intensive activity in energy harvesting research that covers from photosynthetic and biomass to piezoelectric based nanogenerators.

However, the pioneer in using nanowires for energy generation is Z.L. Wang at Georgia Tech. The specific nanopiezotronics technology developed in his group is based on combining the piezoelectric properties of ZnO nanowires with the rectifying characteristics of the Schottky barrier, formed between the ZnO (semiconductor) and a metal. Most recent Wang's group works demonstrate biomechanical to electrical conversion using a single wire generator (SWG), which is able to produce output voltages around 0.1V from human finger tapping or from the body movement of a hamster, or even from breathing and heartbeat of a rat, which demonstrate the potential applicability of NEMS on self-powering implanted nanodevices.

Considering funded energy harvesting research programs in US, National Science Foundation (NSF) launched in 2012 a total of 5 calls:

-Sustainable Energy Pathways (SEP):

"…The SEP solicitation considers scalable approaches for sustainable energy conversion to useful forms, as well as its storage, transmission, distribution, and use. The following Topic Areas illustrate the broad scope of sustainable energy interest areas of this solicitation: **Energy Harvesting & Conversion** from Renewable Resources**;** Sustainable Energy Storage Solutions; Critical Elements & Materials for Sustainable Energy; Nature-Inspired Processes for Sustainable Energy Solutions; Reducing Carbon Intensity from Energy Conversion & Use; Sustainable Energy Transmission & Distribution; Energy Efficiency & Management."

-Solar Energy Initiative (SOLAR):

"…The purpose of the CHE-DMR-DMS Solar Energy Initiative is to support interdisciplinary efforts by groups of researchers to address the scientific challenges of **highly efficient harvesting, conversion, and storage of solar energy**…"

-Energy for Sustainability:

"…Photovoltaic Solar Energy. Solar photovoltaic (PV) devices **harvest and convert sunlight directly to electricity**. Fundamental research on innovative processes for the fabrication and theory-based characterization of future PV devices is an emphasis area of this program. Specific areas of interest include: nano-enabled PV devices containing nanostructured semiconductors, plasmonic materials, photonic structures, or conducting polymers; earth-abundant and environmentally benign materials for photovoltaic devices; photocatalytic or photoelectrochemical processes for the splitting of water into H_2 gas, or for the reduction of CO_2 to liquid or gaseous fuels. The generation of thermal energy by solar radiation is not an area supported by this program, but will be considered by the Thermal Transport Processes program within CBET…"

-Particulate and Multiphase Processes:

"…Innovative research is sought that contributes to improving the basic understanding, design, predictability, efficiency, and control of particulate and multiphase processes with particular emphasis on: novel manufacturing techniques, multiphase systems of relevance to **energy harvesting**, multiphase transport in biological systems or biotechnology, and environmental sustainability…"

-Solid State and Materials Chemistry (SSMC):

"…This multidisciplinary program supports basic research in solid state and materials chemistry comprising the elucidation of the atomic and molecular basis for material development and properties in the solid state from the nanoscale to the bulk…Development of new organic solid state materials, environmentally-safe and sustainable materials, and fundamental studies of novel material and material systems for **efficient energy harvesting, conversion and storage** are encouraged…"

VII.2 In Japan

Japan http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5877098

"*Abstract*: On May 14, 2010, we established an energy harvesting consortium in Japan with 12 member companies. As of March 2011, the number of members increased to 32, and we are continuously receiving inquiries from interested companies and organizations throughout Japan as well as overseas. In an effort to boost Japan's international competitiveness in the field of energy harvesting, we founded a consortium whose goal is to function as a collaborating platform for Japanese companies. We aim to incubate and accelerate new ventures embarked upon by our members as well as stimulate the relevant markets in collaboration with the government of Japan."

VIII Conclusions and follow-up

The development of ZEROPOWER technology has the potential to help Europe to meet many of the Europe 2020 targets especially in the use of energy efficiently and the reduction in costs of healthcare through the development of autonomous sensors that require ZEROPOWER externally. The potential for a high return on investment if Europe invests in appropriate research and development programmes is high with many European companies with the potential to develop and exploit successful technology. FP7-ICT has highlighted ICT as a key engine of growth, with the use of ICT to improve energy efficiency by managing energy demand and use. The energy consumption and carbon dioxide emission from the expanding ICT use, however, is unsustainable and will impact heavily on future climate change. Therefore the development of ZEROPOWER technology is essential if the future societal challenges in Europe are to be met whilst also reducing carbon emissions simultaneously.

VIII.1 Follow-up

As we pointed out at the beginning of the document, in order to attain the ZEROPOWER objective we need to bridge the gap between the energy required by ICT devices and the energy available as the results of harvesting technologies. During the last three years, the ZEROPOWER community has been engaged to coordinate research with respect to the second leg of the bridge: the energy harvesting activity. In the meantime the EC has launched a call entitled "MINECC" (Minimising energy consumption of computing to the limit) funded under the FET Proactive Call 8 (FP7-ICT-2011-8) Objective 9.8. As a result of this call, 7 research projects have been funded, mainly to address the first leg of the bridge. During this year 2013 the ZEROPOWER community set up a novel coordination action, entitled ICT-Energy in order to create a coordination activity among consortia involved in the ICT-Energy field with specific reference to bringing together the existing "Toward Zero-Power ICT" community organized within the ZEROPOWER project and the novel "MINECC" community. The ICT-Energy coordination action started on Oct. 1st 2013.

IX Authors and Acknowledgement

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