Energy Harvesting
An EPSRC Funded Network

EPSRC
Engineering and Physical Sciences Research Council

Scaling Effects for Micro and Nano Scale Energy Harvesters

a roadmap to new research challenges

Produced by:

The Energy Harvesting Network

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Executive Summary

This report and accompanying roadmap have been developed by the Energy Harvesting Network to identify a new generation of research challenges in the field of energy harvesting. The purpose of this is to inform funding agencies of emerging areas of science and engineering that will require support and to act as a catalyst for bringing together multidisciplinary teams to develop proposals to tackle these research challenges. As the third in the series of such exercises this study focuses specifically on scaling effects for micro- and nano scale energy harvesters. In contrast to the previous two, which addressed the well-defined applications of 'Human Power' and 'Structural Monitoring', this workshop primarily concerns science and technology advances.

The scope of this workshop covers the application of micro electro mechanical systems (MEMS) / nanoelectromechanical systems (NEMS) to energy harvesting and in particular explores the scaling effects when reducing these devices in size. MEMS/NEMS are having a great impact on performing measurements, signal conditioning and actuation. At the same time they are an attractive approach for the mass production of both kinetic and thermal energy harvesters, which could be used to power external systems or potentially realise self-powered microelectronics. Manufacturing can reach the micro/nano scale either from the top down, by 'machining' to ever smaller dimensions, or from the bottom up, by exploiting the ability of molecules and biological systems to 'self-assemble' tiny structures. Importantly, scaling effects will influence the fundamental energy available from such devices, the efficiency with which it can be harvested and the practical constraints of the micro/nano fabrication processes must also be considered.

In an effort to define the new research challenges required to deliver on the potential of energy harvesting, the workshop aimed at establishing what is reasonable to expect in terms of fundamental physics, fabrication processes, electronics, ambient sources etc. and which MEMS/NEMS technologies have the most promise to practically address the energy needs.

The roadmap was developed primarily through a workshop that brought together expert opinion from both academia and industry. Expertise included various energy harvesting technologies and approaches as well as materials, electronics, wireless sensor networks, standards and energy storage. In addition, some participants had specific MEMS design and fabrication expertise. The roadmapping process mapped out over the next 10 years the technology developments and underpinning science required to enable the realisation of a vision for dependable scaled-down energy harvesting devices that take advantage of advances in MEMS/NEMS technologies and can draw upon a range of ambient energy sources to aid the powering of embedded or retrofitted sensor and actuator systems.

In order realise the potential of energy harvesting at small scale, the fundamental approaches involve investigations in engineering nanocomposite materials with new functionality or improved performance over traditional materials and using new materials as coatings on existing devices which may lead to improved performance.

Integrating the sensing material with the generating material could also be a way to make a better system i.e. using a multifunctional material. Other possibilities are to develop intelligent systems that modify their harvesting based on the environment that it is harvesting in.

For thermoelectric harvesting microfluidic cooling systems could improve the applicability of the technology in a 10 year horizon. Vibration energy harvesting would benefit from inertial energy harvesters that have variable resonant frequencies and that can adjust damping to accommodate variations in drive amplitude (non-linear or adaptive devices) in a 7 year horizon. Lower stiffness materials with high fatigue strength and higher density materials for inertial masses would both reduce resonant frequencies to those more commonly found in application environments (within 5 years). The applications that would benefit from these developments would be machine or transport based initially and then human application at a later date (beyond the next 10 years).

Technology development is needed in a range of areas to realise the potential of energy harvesting at small scale. Some highlights include improved shape and complexity during 3D micro fabrication by using novel lithography or flexible substrates; tools for handling and assembly at small scales; low power fast analogue circuits (<10ns delay); improved transducer materials (e.g. Ferroelectrets); increased coupling using active power conditioning circuits; small signal measurement to ssupport metrology standards for energy measurement at small scales; and iidentification of critical commercial pull applications and production of applications matrix for energy harvesting sensing systems and design tools

Major areas of underpinning science that will need to be addressed include investigation of potential benefits of nanowires, 1D electronics and graphene and carbon nanotubes to energy harvesting; non-linear effects for chaotic / wideband sources; miniaturisation using monolithic silicon structures; high quality spinning bearings to support gyroscopic power generation with MEMS; energy storage components suitable for small scales; circuits with minimal start-up leakage; modelling tools for designing micro harvesters; and environmentally friendly and safe materials as well as materials characterised by low stiffness; high reliability and density.

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Workshop participants and other contributors

Simon	Aliwell	Zartech Ltd
Carl	Anthony	University of Birmingham
Steve	Beeby	University of Southampton
Harold	Chong	University of Southampton
John	Collins	Technology Strategy Board
Rob	Dorey	Cranfield University
Min	Gao	Cardiff University
Carlos	Huggins	ESP KTN
Costis	Kompis	Vodera Ltd
Elena	Koukharenko	University of Southampton
Michael	Kraft	University of Southampton
Tim	Leeder	Technology Strategy Board
Xiao	Liu	Brunel University
Douglas	Paul	University of Glasgow
Leo	Poll	Philips Innovation Services
Bernard	Stark	University of Bristol
Yoshishige	Tsuchiya	University of Southampton
John	Tudor	University of Southampton
Tony	Vilches	Brunel University
Dick	Wallis	Position Systems Ltd
Patrick	Waters	Nuovatec Limited
Paul	Weaver	NPL
Jize	Yan	University of Cambridge
Kai	Yang	University of Southampton
Eric	Yeatman	Imperial College London

Introduction

The Energy Harvesting Network is an EPSRC funded network of UK academic and industrial researchers and end-users of energy harvesting (EH) technology. Specifically, the primary objectives of the Network are to:

- Define new challenges in EH research and address them through new multidisciplinary teams.
- Facilitate the interaction and mobility of EH researchers.
- Ensure wide dissemination of the advances in the science and the developments of the technology.

Discussions with EPSRC indicated that new challenges would be required if they are to continue to fund research in the area of energy harvesting.

In defining a new generation of research challenges the aim is to explore applications and approaches of significant potential where incremental improvements of current generations of EH technology will be insufficient. In doing so, and in eventually addressing the new challenges through multidisciplinary research teams, the aim is to involve people from a wider set of backgrounds than are currently engaged in EH research.

This report describes the outputs of the third workshop in the series which was aimed at defining the research challenges in the area of scaling effects for micro and nano scale energy harvesters.

The Steering Board of the Energy Harvesting Network discussed a number of options for new and challenging areas of research and decided on scaling effects for micro and nano scale energy harvesters for this third workshop. This theme was judged highly ambitious in terms of research challenge and the broad range of potential applications which it can underpin as well as offering an opportunity to create completely new synergies for the energy harvesting community.

The scope of this particular workshop included scaling effects for micro and nano scale energy harvesters. These may cover design, characterisation, production and application of structures, devices and systems by controlling shape and size in scales, which cover the size range from approximately 1 to 100μm for micro and 1nm to 100nm for nano, respectively.

Although discussions at the workshop were wide ranging and included developments relatively close to deployment, the main focus is on identifying the low technology readiness level challenges (<TRL 4).

Approach / methodology

Who should read this?

This report is aimed at informing funding agencies (e.g. Research Councils and the Technology Strategy Board) of the new, challenging areas of energy harvesting that should be addressed so as to help inform their programmes. It is also aimed at researchers from a broad set of disciplines interested in opportunities of energy harvesting at very small scale by

- applying their MEMS/NEMS expertise to these challenging areas, or
- developing such small scale EH devices themselves.

This report should inform them of the specific challenges to be met and the interdisciplinary skills required to do so. It is anticipated that this report will be the catalyst for a series of collaborative project proposals.

Overall approach

A workshop was designed to help facilitate the definition of the new research challenges. Participants from a wide variety of disciplines were invited with representation from both academia and industry. These covered expertise in a range of energy harvesting technologies and approaches, materials, nanofabrication techniques, electronics, wireless sensor networks, metrology and energy storage. The aim was to use the input of this group to understand the various developments (scientific and technological) that will be required in order to realise the defined vision and to help generate a series of specific research challenges that if addressed would move the field forward substantially.

The workshop agenda (see Appendix 1) included short presentations and discussions to get delegates thinking about the practical challenges of implementing and operating micro and nano scale energy harvesters in relation to the power requirements of the sensing systems. The facilitated workshop sessions then debated key issues expected to influence developments in the coming years and the science and engineering research challenges that will need to be addressed. This enabled the roadmap to be constructed and these acted as the basis for defining a series of research challenges – the ultimate objective of this exercise.

The information gathered was validated through additional research and through further discussions with the Energy Harvesting Network's Steering Board and other identified experts.

The roadmap

A roadmapping methodology was used to frame the discussion and ensure that the exploration of the gaps between current capability and future needs was thorough. In building the roadmap the task and structure was broken down into the following:

- Definition of a vision
- Exploration of the relevant existing EH techniques to ensure that the roadmap is not bound by what is currently thought possible
- Exploration of the drivers
- Outlining of the potential applications and areas of impact
- Exploration of the technology developments that are due to occur over the relevant period

- Exploration of the underpinning science and engineering that will be needed

The timeline for the roadmap was 10 years from the present (until 2022) with timing generally being defined as when something becomes mainstream rather than the first instance of someone working on the topic.

Scope & limitations

This roadmapping exercise has been designed to specifically focus on scaling effects for micro and nano scale energy harvesters. These may cover design, characterisation, production and application of structures, devices and systems by controlling shape and size in scales, which cover the size range from approximately 1 to 100μm for micro and 1nm to 100nm for nano, respectively.

Larger-scale microsystems are more mature and being pursued very actively in the UK and around the world on a more immediate timescale. Although there has been much recent interest in nanotechnologies and nanoscience with successful deployments in the form of actuators and sensors, radiating energy microdevices (eg. antennas), and controlling/processing integrated circuits, there has been very little focus on how energy harvesting might benefit from its advances. There is thus very little practical experience to draw upon. Nevertheless, this exercise has drawn upon a very diverse group mainly from academia who covered topics such as the fundamental limits and physical transduction principles, power conditioning electronics and energy storage, micro and nano fabrication processes as well as metrology at the micro and nano scale. It may have benefited from more involvement of industry specialists, however it is recognised that there are very few people with such skills.

The roadmap itself is not intended to represent an exhaustive development plan, as is the case with some industry or company specific roadmaps. Its chief purpose is to frame a structured discussion. In this way it is hoped that the result will be a comprehensive coverage of the needs and challenges that leads to the identification of the current gaps in capability and the research themes which would help to fill them.

In terms of the applications of energy harvesting included the scope was deliberately kept broad since micro and nano scale technologies are key enabling technologies usually embedded into a larger scale component or system. Aspects of key importance at these scales include materials, manufacture, measurement and integration.

All energy harvesting techniques are considered in scope including those not currently viable.

Regarding terminology, because the list of terms used to describe the fields of MEMS and NEMS are extensive (e.g. microsystems, micromachines, nanosystems, nanoscience etc) in this document we shall use some of them interchangeably depending on the context.

New Trends in Engineering and Science: Micro- and Nano Scale Systems

Micro- and nanoelectromechanics are based upon fundamental theory, engineering practice and leading edge technologies in fabrication of micro- and nanoscale systems, subsystems, devices and structures which have dimensions of micrometres or nanometres. They have experienced phenomenal growth over the past few years due to rapid advances in theoretical developments and experimental results.

Table 1 illustrates some of the landmarks in the history of MEMS and NEMS.

Table 1 Landmarks in the history of MEMS and NEMS[1]

1940s	Radar drives the development of pure seminconductors
1959	Richard P. Feynman's pivotal lecture "There's plenty of room at the bottom"
1960	Invention of planar batch-fabrication process
1964	Production of the resonant gate transistor with meal-beam micromachining, the first batch-fabricated MEMS device
1970	Invention of the microprocessor
1979	Development of the first micromachined accelerometer
1982	Invention of the scanning tunnelling microscope
1984	Joint fabrication of MEMS and integrated circuits using the polysilicon surface micromachining process
1986	Invention of the atomic force microscope
1991	Discovery of the carbon nanotube
1991	Fully integrated single chip accelerometer by Analog Devices
1996	Technique for producing carbon nanotubes of uniform diameter
2008	1 billion sensors produced by a single company (Bosch)
2010-	Number of MEMS devices and applications continually increases

The development and deployment of MEMS and NEMS are critical to the economy and society, because they lead to major breakthroughs in a vast range of application domains as illustrated by the Table 2.

[1] Based on John A. Pelesko and David H. Bernstein, Modeling MEMS and NEMS, CRC Press, 2002.

Table 2 Summary of technologies within market sector areas[2]

Market area (market revenue in $m 2007), (potential revenue $m in 2015)	Sub areas (actual 2007 market revenue in $m), (2015 predicted market revenue in $m) (Nanoposts nanomaterials and markets, 2008 report)			
Aerospace and defence $323.5m, **$3,768m**	Nanocomposites $27m, **$910m**	Electronics & sensors $58.5m, **$182m**	Nanocoatings $165m, **$1,880m**	Energy devices and fuel additives $45m, **$376m**
	Smart materials $28m, **$420m**			
ICT $585m, **$41,402m**	Carbon nanotubes $45m, **$800m**	Nanowires $30m, **$900m**	Nanoscale memory $250m, **$21,000m**	Printed electronics $150m, **$12,000m**
	NEMS $10m, **$520m**	Spintronics $50m, **$6,000m**	Quantum dots $50m, **$650m**	
Energy $90m, **$3615m**	Photovoltaic film coatings $30m, **$760m**	Fuel cells and batteries $30m **$1,650m**	Thermoelectric materials $5m, **$445m**	Aerogels $25m, **$760m**
Life Sciences and Healthcare $145m, **$5,670m**	Nanoscale biosensors and imaging $20m, **$1,220m**	Nanocoatings on surfaces and implants $50m, **$1,800m**	Nanoparticulate drug delivery $75m, **$2,650m**	
Construction $66m, **$1,672m**	Nanoscale sensors and smart materials $1m, **$212m**	Nanocomposites $5m, **$375m**	Nanocoatings $50m, **$750m**	Additives to concrete $10m, **$335m**
Automotive $404m, **$7,134m**	1. Nanocoatings $181m, **$2,451m**	2. Composite fillers $150m, **$2,106m**	3. Additives in catalysts and lubricants $69m, **$1,740m**	4. Fuel cells $25m, **$450m**
	5. Smart materials $15m, **$387m**			
Textiles $122m, **$2,170m**	Coatings $120m, **$1,850m**	Smart materials and sensors $1m, **$125m**	Nanofibres/nanotubes $2m, **$195m**	
Environment and water $86m, **$3,885m**	Nanoporous membranes $41m, **$975m**	Chemical and bio nanosensors $5m, **$490m**	Nanoparticles $29m, **$2,000m**	Nanocoatings $11m, **$420m**
Agriculture, food and drink $265m, **$3,210m**	Nanosensors $2m, **$360m**	Encapsulation $3m, **$320m**	Nanocoatings $40m, **$495m**	Nanocomposites $180m, **$1,580m**
	Nanoporous membranes $40m, **$455m**			
Consumer goods and household $188m, **$6,225m**	Nanocomposites $67m, **$1,248m**	Nanocoatings $70m, **$1,500m**	Nanoparticles $51m, **$3,477m**	
Brand and product security $30m, **$2,650m**	Nanocoatings $10m, **$1,000m**	Nanoparticles $20m, **$1,650m**		

In the case of energy harvesting there are a number of potential energy sources to be harvested such as thermal, vibrations and electromagnetic by the highly pervasive MEMS/NEMS technologies.

Vision

The vision set for the workshop was:

Dependable scaled-down energy harvesting devices that take advantage of advances in MEMS/NEMS technologies and can draw upon a range of ambient energy sources to aid the powering of embedded or retrofitted sensor and actuator systems.

[2] Nanoscale Technologies Strategy 2009-12, Technology Strategy Board, 2009.

Drivers

Many of the drivers for the energy harvesting in this domain are the drivers for the embedded or retrofitted battery-less sensors and actuators. The main drivers are economic, social, technical and policy and all are closely connected.

Economic Drivers include:

- Smaller, cheaper (cost per function decrease), lighter and faster devices with greater functionality, using less raw material and consuming less energy
- Batch manufacturing (high volume, low cost production)
- Considered as a set of enabling technologies for a wide range of market applications: chemistry and materials, biotechnology – pharmaceutical, healthcare (eg. lab-on-a-chip diagnostics), security/defence, environment, consumer products, construction, transport
- Battery lifetime results in expensive battery changes for retrofitted sensors and is impractical for embedded sensors – particularly impractical if sensing is to become ubiquitous
- Changing business models and servicing responsibility
- (-) Nanotechnology is an expensive science in terms of required experimental hardware
- (-) Require large capital investment to successfully seed, produce and commercialize

Social Drivers include:

- Promise to contribute towards solutions for some of the key societal challenges eg. support ageing population, environmental change, global security, energy, food security and the digital economy
- Increasing resistance to proliferation of the use of batteries
- (-) Conservative nature of the some industrial sectors

Science / Technology Drivers include:

- Advanced infrastructure, materials and design tools available to implement special processes (micromachining, functional thin films, wafer stacking)
- Beyond CMOS disruptive energy efficient technologies and devices (nanowire electronics, steep slope devices, carbon and graphene nanotubes, spine electronics, memristive devices, photonics, synthetic photovoltaic cells etc)
- Techniques for integration with ultra-low power electronic circuits and sensors
- Better understanding of energy efficiency limits
- Metrology and instrumentation expertise; Metrology & Standards
- Proliferation of autonomous systems featuring sensing, computation and communication
- availability of hybrid harvesters

- (-) Continued need for energy storage devices

Policy Drivers include:

- Increasingly common battery and waste management laws in Europe
- (-) Funding has often been spread too thinly (e.g. Micro and Nano Technology Manufacturing Initiative.)
- Greater industrial awareness and understanding of the scope for nanotechnology to enhance products and performance
- R&D driven collaboration: Engagement with global partners e.g. participation in EC projects.

Fundamental Limits

One of the key questions raised during the workshop is how much can the existing state of the art be improved upon and over what time scales. In other words, with what efficiency could energy be harvested in the future, considering the fundamental limits for useful energy transduction at very small scale.

A keynote lecture informed the delegates that basic mechanics set strict limits on achievable power from inertial harvesters and that ultimate power density drops as devices shrink. Form factor, resonance and choice of transduction are important considerations and rotating harvesters can offer some ways around the basic limits.

Thermoelectric devices lend themselves to miniaturisation and become more efficient as they are scaled down. Electromagnetic devices however face significant scaling law challenges in reducing their size. The amount of energy that can be harvested falls off rapidly with any reduction in both the size of the vibrating counter mass and in the distance through which it displaces. Since MEMS manufacturing lends itself to planar processes, as the device gets smaller and smaller it becomes more difficult to create designs that actually allow sufficient displacement. In addition, there are scaling limitations due to the challenges of integrating coils in MEMS fabrication and due to the lower magnetic properties for micro-fabricated versus bulk magnets. Electrostatic energy harvesting is on the other hand compatible with MEMS technology although the need for an initial external charge and the limited power density at micro-scale are issues. Piezoelectric devices are amenable to micro-scale manufacture but where used in vibrating cantilever form are also subject to scaling law effects due to reductions in the inertial mass dimensions and potential displacement. Being a planar technology photovoltaic techniques scales according to collecting area. The minimal useful photovoltaic panel dimensions are determined by the efficiency of the energy conversion and the amount of light available. For indoor lighting applications there is still sufficient light to power home automation applications e.g. window sensors, temperature sensors etc with panels of only a few cm2.

It is important to note that straightforward ‘efficiency’ is not the correct factor/term to use because the achievable efficiency will be quite different for different technologies or harvesters as a whole. Simply there would not be one magic number to describe it. Instead researchers should consider terms such as: ‘foot print efficiency’ and ‘effectiveness’ or ‘effectiveness limit’ because these terms can also link some of the form factors and operational constraints – based on where the energy harvester will be deployed. Potential form factors could be: credit card, match box, drink can, shoe heel, pizza box or existing battery form factors: e.g. AA/9V. User requirements are linked to size, storage capacity, power density and cost. Therefore, in terms of approach it is better to start with application, then define effectiveness and subsequently link it to standard conditions.

With regards to **vibration energy harvesting**, **t**he coupling coefficient electromagnetic and electrostatic of devices scales at a different rate. The electrostatic conversion mechanism is more efficient for transducer devices with a typical MEMS (<100mm3). On the other hand, an electrostatic transducer device may be outperformed by an electromagnetic transducer for larger device sizes (>1cm3). Thus, if miniaturisation is a key driver due to space limitations of large low cost production, electrostatic MEMS energy harvesters are the preferred choice. At present MEMS devices have an effectiveness of ~5%. With improvements in materials, use of non-linear structures, higher density inertial masses etc. this could increase up to 50% in some applications. The time scale for these developments will be up to 10 years. For microscale resonant harvesters, around 50% was going to be the maximum that could realistically be extracted from the resonator. So getting the energy harvested in the resonator up is the key issue. 3D fabrication technology could allow better use of the volume compared with 2.5D MEMS devices. In summary, electromagnetics do no scale down well in size, but electrostatics scale favorably and piezoelectrics are largely unaffected. Both piezoelectric and electrostatic are suitable for microscale applications with piezo devices being far easier at present to fabricate.

For t**hermoelectric**, assuming a 10^{o}C temperature gradient, at present 0.6% efficient giving 10mW/cm3. This could be improved by a factor of 2, timescale > 5 years.

For **piezoelectric** based harvesters improvement of the materials by micro/nano engineering the structure of the materials could be the key way to improve performance. This is also the case for thermoelectric but this is already a major research area.

For **solar** changing the technology completely to a bio inspired photosynthesis type mechanism could see big improvements.

Fuel cells scavenging energy from body fluids could have better performance for certain applications.

Power conditioning electronics: research at the device level to design components with minimum energy consumption rather than performance. At present for a harvester producing 50 mW, 50% is lost in the circuitry, this could be reduced to 20 % lost over the next 10 years. Indeed, short-term improvements are more likely to come from optimisation of the system and a systems approach to developing the harvester with the power management and specific application are likely to yield bigger initial improvements.

Integration of Energy Harvesters alongside Electronics and MEMS

Microtechnology has had already a major impact on shrinking the size of electronic components which are referred to as microelectronics. Figure 1 shows the comparative evolution of eight prominent chip technologies over the last seventy years. As a result, the size of electronics is rarely the issue while energy harvesters have today a finite size. In most cases there is no need for monolithic integration with silicon. That would indeed reduce overall system size but economically some system blocks may always be better off as separate elements. For some sensors that require measurement of very small capacitances then there may be free real estate to house the harvester. Otherwise one would be unnecessarily using expensive silicon chip real estate. In general, it makes good sense to integrate energy harvesters with the target system and then fit electronics around the energy harvester, potentially integrate non-silicon electronics around it. Considering organic electronics a major technical challenge is printing electronics onto the energy harvester's packaging.

In other cases, the co-location of the harvester and electronics may highlight aspects of the harvester design that would benefit the power conditioning electronics making it simpler and more efficient.

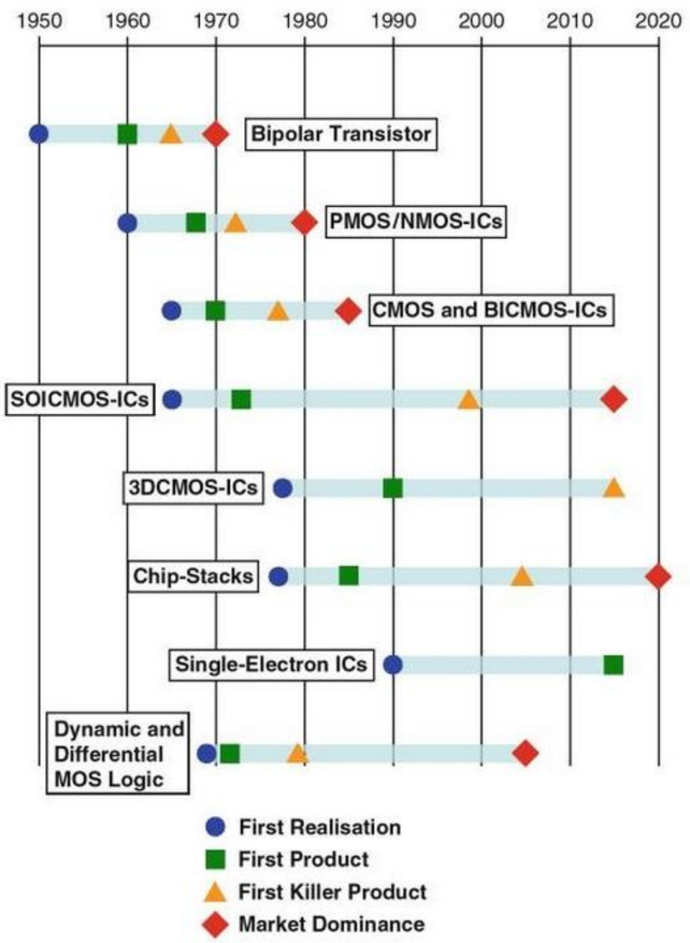

Figure 1 The life cycles of 8 prominent chip technologies [3]

Fabrication processes ought to be looking at integrating novel materials into the harvesters or power systems i.e. radioactive, biological cells. Technically, thermoelectric devices are able to be integrated with electronics now but at extra cost and complexity (reduced yield). At present there is no clear market to drive the development of this.

Piezoelectric vibration energy harvesters made with Aluminium Nitride (AlN) are compatible with standard IC technology today and the issue again is additional cost and complexity.

[3] Bernd Hoefflinger (Ed), Chips 2020: A Guide to the Future of Nanoelectronics, Springer, 2012.

A practical example of device integration is the production of hybrid vibration energy harvesters e.g. piezoelectric and electromagnetic to provide a separate channel for switching signals for the power conditioning electronics. Flexible electronics – electronics that can be used in multiple environments and products, e.g. a common electronics platform that can also be used with multiple energy harvesting devices that themselves can be used in multiple environments.

Flip chip bonding is a promising solution. 3D packaging technology would be key and therefore research into cheap packaging technologies is needed.

So since monolithic integration is not needed, systems integration becomes key. What is needed is an integrated co-design strategy that considers the harvester, the application, the power management and all the packaging in one. Systems integration also includes addressing the protocols used for wireless communication to reduce their power. There is also a need for very low power protocols as a universal standard, i.e. reducing the power requirements of the application.

Full integration should not be seen as panacea. Depending on the target application cost may be a decisive factor particularly if a system can be implemented with existing fabrication. In general, the timeline for this to be achieved depends on the scale. For a large assembly it is already possible but for small scale assemblies where integrated fabrication is required a development period of 10 years or more may be required.

Taking the other developments forward (i.e. new materials for harvesters and the development of low energy IC designs) these issues of compatibility will need to be re-evaluated and solved. Again, the time horizon for these developments will be 10 years plus.

Impact of Fabrication Processes on Transduction Efficiency

Fabrication processes can cause materials changes at the small scale via decreases in properties due to constraint imposed by neighbouring materials vs evolution of new behaviour. There are opportunities to build improved energy harvesters by reusing facilities that have been ‘abandoned’ by the electronics industry. It remains to be established whether 2.5D limitation impose performance limitations.

Multiple small devices can be synchronised during fabrication to achieve higher power. Issues having an impact are the ohmic losses as size scale decreases and the parasitic capacitances due to greater substrate influence. Leakage/loss becomes critical for transmission and storage.

Below we discuss how specific types of energy harvesting elements may be impacted by fabrication processes.

Thermoelectric elements can be fabricated with sufficient resolution. At mm and µm scale with powers <<1W, thermoelectrics are more efficient than thermodynamic engines. Impedance matching, maximum power point tracking and heat sinking are key for thermoelectrics. Key process development is required for yield and cost requirements. Research into new materials, and their associated fabrication processes and improving the ZT figure of merit timescale is also required. A horizon of 5 years applies to these developments.

Electromagnetic vibration energy harvesting at present is limited by the constraints imposed by the fabrication process on the properties of the coil – resistance increases faster than electromagnetic coupling. To overcome this lower resistivity, conductors are required and/or fabrication process that enable high aspect ratio metal tracks to be reliably patterned and isolated from each other (e.g. 10μm x 10μm track, 1μm spacing) and for the process to be repeatable on additional layers to build up a sufficient number of turns. This process development would take 3 years. In addition to this, to make a truly integrated EM harvester, the magnetics need to be deposited using thin/thick film techniques. At present, such films are ~50% weaker than bulk magnetic materials. Improved materials and process for integrated magnets are therefore also required and this could be done in the next 5 years.

Piezo materials that do not have the drawbacks associated with the ceramic materials, such as aging, fatigue and loss of polarization, would make it easier to extract the energy. Also moving to more eco-friendly materials in the future will be needed as there are increasing pressures to banish PZT.

Piezoelectric vibration energy harvesting requires development of higher activity materials and processes for their deposition. In addition to improved piezoelectric properties, improved mechanical properties (e.g. elasticity, fatigue strength) would also be beneficial since these limit the amplitude of the inertial mass and lifetime of the harvester. The expected timeframe for these developments is 5-7 years.

Electrostatic vibration energy harvesters would benefit from electret material and process development and designs and processes that are resistant to stiction. Improved flexible dielectric materials and associated processes may also be beneficial. The estimated timescale for these developments is 3 years

Although most energy harvesters are solid discrete objects, advantages can be seen in moving to materials that are more fabric like. This would increase the area for harvesting and make a big difference to wearable harvesters as harvesting distributed over the whole human body. So looking at flexible polymer based harvesting systems has several benefits.

Power Gap between Devices and Applications

A priority is to reduce the power demand of applications. This could be achieved by incorporating smarter wireless protocols, much lower power electronics for sensor nodes, etc.

Device performance improvements could be addressed through investigating several areas including:

i) Engineering nanocomposite materials with new functionality or improved performance over traditional materials.

ii) Using new materials as coatings on existing devices which may lead to improved performance i.e. metamaterials, phase change materials, new combinations of materials.

Integrating the sensing material with the generating material could also be a way to make a better system i.e. using a multifunctional material.

Other possibilities are to develop intelligent systems that modify their harvesting based on the environment that it is harvesting in, i.e. switches from resonant to thermoelectric or self-tunes to the frequency. Intelligent or adaptable harvesters are better suited to ‘exotic’ locations (e.g. aeronautic, rail, vehicular, human applications) where the characteristics of the energy sources, and also the type of energy source, will change. These are far more demanding than ‘standard’ environments e.g. industrial installations that have fixed frequencies to target.

For **thermoelectric harvesting** the practical considerations of maintaining the temperature gradient is a key issue. Microscale harvesters still require conventional relatively large heat sinks which negate the size benefits. Microfluidic cooling systems could improve the applicability of the technology (10 years). Applications for thermoelectric energy harvesting are being driven by the automotive sector at present. Applications on other machinery, and buildings based applications would benefit from smaller total package size.

Vibration energy harvesting would benefit from inertial energy harvesters that have variable resonant frequencies and that can adjust damping to accommodate variations in drive amplitude (non-linear or adaptive devices) (7 years). Lower stiffness materials with high fatigue strength and higher density materials for inertial masses would both reduce resonant frequencies to those more commonly found in application environments (5 years). The applications that would benefit from these developments would be machine or transport based initially and then human application at a later date (10 years +).

Key research challenges

The exercise to build the roadmap formed the main input to a workshop session on defining specific research challenges. What follows is the output of these discussions in the form of a number of research challenges that the participants felt would be worth building collaborative projects around. Since the challenges varied in TRL level and the extent of academic versus commercial involvement they have been classified as either suitable for the Engineering & Physical Sciences research Council remit or the Technology Strategy Board's remit.

Technology Strategy Board (TRL 4+):

- Micromachining of 3D mechanical structures
- Improved shape and complexity during 3D micro fabrication by using novel lithography or flexible substrates
- Tools for handling and assembly at small scales
- Low power fast analogue circuits (<10ns delay)
- Hybrid MEMS/NEMS energy harvesting technologies by combining sources, control and storage elements
- Design of multi-purpose energy harvesting components and infrastructure elements
- Microfluidic cooling for thermoelectric devices
- Improved transducer materials (e.g. Ferroelectrets)
- Increased coupling using active power conditioning circuits
- Small signal measurement to support metrology standards for energy measurement at small scales
- Identification of critical commercial pull applications and production of applications matrix for energy harvesting sensing systems and design tools

EPSRC (TRL 1-3):

- Investigation of potential benefits of nanowires, 1D electronics and graphene and carbon nanotubes to energy harvesting
- Investigation of non-linear effects for chaotic / wideband sources
- Further miniaturisation using monolithic silicon structures
- Synthetic photovoltaic cells and synthetic photosynthesis
- High quality spinning bearings to support gyroscopic power generation with MEMS
- Energy storage components suitable for small scales
- Circuits with minimal start-up leakage
- Modelling tools for designing micro harvesters
- Environmentally friendly and safe materials (no Pb/Cd/Bi/Te etc). Low stiffness high reliability structural MEMS materials to achieve low frequencies; High density materials and methods of processing for inertial masses to improve power density and reduce frequencies; and High reliability (i.e. long lifetime) materials (structural and transducer).

These will be pursued through collaborative R&D projects after discussions with relevant funding stakeholders.

Skills, people, resources

The UK has a number of strengths in the domain of MEMS/NEMS, including a strong academic sector; extensive business support network (Nano KTN and MNT facilities, academic centres of excellence); instrumentation expertise and a globally leading role in metrology and standards.

Given that the fields of MEMS and NEMS are truly interdisciplinary this presents a further challenge for the energy harvesting community in terms of accessing suitable skills. Mastery of materials science, mechanics, electromagnetism, circuit design, and numerous other subjects is often required before breakthroughs can be achieved. It is recognised that some of these skills are hard to find in individual disciplines and curriculum changes or new professional education programmes may be necessary to provide them to the next generations of engineers involved.

Despite MEMS/NEMS showing potential for application in most energy harvesting approaches it is essential to establish where commercial advantages are genuinely to be found. For this it is vital to be aware of the supply chain ranging from research facilities to component manufacturers and system providers.

As MEMS/NEMS underpin global industries, international collaboration is essential for their exploitation. The provision of this could come through international projects such as EU funded GREEN SILICON (Generate Renewable Energy Efficiently using Nanofabricated Silicon); NANOPOWER (Nanoscale energy management for powering ICT devices) and SINAPS (Seminconducting Nanowire Platform for Autonomous Sensors). Related activities at European level are coordinated by the ZEROPOWER action project.

Standards are needed in a number of areas to promote adoption of MEMS/NEMS energy harvesting, for example related to performance comparison of energy harvesting devices. In the UK NPL has particular expertise in issues related to metrology and standards in the context of energy harvesting currently leading the Metrology for Energy Harvesting activities of the European Metrology Research Programme (EMRP). The ISA100.18 Power Sources Working Group of the International Society of Automation is preparing standards and information documents on power sources for WSNs. They are defining performance specifications so that users can compare different harvesters and choose the optimum power source for each application. The aim is to stop wild claims, help integrators to adopt the technology and to meet the information needs of the users. This working group is also defining standards for power module interchangeability by specifying connection options.

Appendix 1: Workshop agenda

3rd Research Theme Workshop - MEMS/NEMS Energy Harvesting
Friday 2nd December 2011University of Southampton, UK

The Network is currently organising the 3rd research theme workshop, concerned with the application of MEMS/NEMS technology to the topic of energy harvesting and in particular explores the scaling effects when reducing these devices in size.

MEMS/NEMS technology is an attractive approach for the mass production of both kinetic and thermal energy harvesters which could be used to power external systems or potentially realise self-powered microelectronics. However, scaling effects will influence the fundamental energy available from such devices, the efficiency with which it can be harvested and the practical constraints of the micro/nano fabrication processes must also be considered.

The workshop will bring together expert opinion from both academia and industry so as to explore the boundaries of micro and nano scale energy harvesting and the opportunities that may arise at the nano scale (e.g. quantum effects). The agenda (see below) includes short presentations to get delegates thinking about the challenges and facilitated workshop sessions will debate the specific technology developments and scientific advances that will be needed to realise the vision of these applications. The key findings will form the basis of a publicly available roadmap that will illustrate technology developments and underpinning science required to realise practical MEMS/NEMS energy harvesters over the next decade.

Agenda	
9.30	Registration & coffee
10.00	Introduction - What are we trying to do and what is the process? *Professor Steve Beeby, University of Southampton*
10.10	Key Note Talk - Fundamental energy calculations, physical transduction principles and the effect of scaling and review of existing state of the art *Professor Eric Yeatman, Imperial College London*
10.40	Power conditioning electronics and energy storage for MEMS/NEMS energy harvesters *Dr Bernard Stark, University of Bristol*
10:55	Coffee Break
11.10	Metrology at the micro and nano scale *Dr Paul Weaver, NPL*
11.30	Facilitated Workshop - Technological Advances to Realise the Vision *Small Groups*
12:30	Lunch, Tour of the Cleanroom, and Networking
13:30	Key Note Talk - State of the art in micro and nano fabrication processes *Professor Rob Dorey, Cranfield University*
13.50	Thermoelectric Energy Harvesting *Professor Douglas Paul, Glasgow University*
14.10	Facilitated Workshop - Underpinning Science and Engineering to Realise the Vision *Small Groups*
15:40	Wrap up and Next Steps
15.45	Close