Energy Harvesting
An EPSRC Funded Network

EPSRC
Engineering and Physical Sciences
Research Council

Energy Harvesting for Structural Monitoring

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 second in the series of such exercises this study focuses specifically on energy harvesting for the powering of sensors for structural monitoring of fixed civil infrastructure. Examples of applications areas include buildings, bridges, tunnels, dams, offshore platforms, pipelines, mines, embankments etc.

The roadmap was developed primarily through a workshop that brought together expert opinion from both academia and industry. Expertise included energy harvesting technologies and approaches, construction sector knowledge, materials, electronics, wireless sensor networks, standards and energy storage. 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 robust and easy to install energy harvesting devices that can draw upon a range of ambient energy sources to aid the powering of embedded or retrofitted structural monitoring sensor systems for the appropriate lifetime of fixed civil infrastructure.

Technology development is needed in a range of areas to realise the potential of energy harvesting for this sector. Some highlights include development of a more systems level approach to take advantage of the step change reductions in power requirements as well as the ongoing issues with power management and energy storage. Total cost models will be needed to demonstrate value to the construction industry. Devices will also need to be designed for retrofit and periodic technology refresh. There is also a need to develop approaches to determine the available harvestable energy in various structural monitoring scenarios. New energy harvesting technologies and approaches are likely including the eventual adoption of low cost MEMS harvesters, the demonstration of practical feasibility for broadband and non-resonant vibration harvesters and the use of new materials such as magnetostrictive and lead free piezoelectric materials. Continued development is needed in control technologies to ensure more efficient harvesting and storage. Over the longer-term improved packaging and demonstrated long term deployment in harsh environments will strengthen the reliability claims of energy harvesting. Finally, it is likely that completely new approaches to energy harvesting that are incorporated into the structure itself will emerge. These include potentially harvesting EMF by exploiting clever design of the steel reinforcement loops set in concrete and exploiting processes like the galvanic sacrificial protection of steel infrastructure.

Major areas of underpinning science that will need to be addressed include development of a range of software tools. Such tools include ones to accurately predict power available during site surveys, tools to optimise harvester performance and sensor node power usage and tools to synthesise optimum energy harvesting and power conditioning circuits. Work is needed to develop new sensing strategies such as ‘compressed sensing’ so as to further reduce the required power. MEMS technology advances are required to deliver combined sensor-energy harvester devices, completely integrated and with ultra-low power requirements. Work is also needed to characterise the energy harvesting capability and long-term resilience of new materials e.g. magnetostrictive materials. Microfluidics requires investigation for its microgeneration possibilities. New combinations to form hybrid energy harvesters require attention including harvesters combined with RFID-like capability. The components and structure of buildings themselves will need to be examined for their potential to provide energy. New approaches to energy storage are needed to overcome the limitations of secondary batteries and supercapacitors. Finally, research is required into energy transducers that may be able to convert one form of energy into another for easier or more efficient harvesting.

A series of specific research challenges were identified from this roadmapping exercise. These include:

- Integrated system design approaches for energy harvesting
- Harvesting energy from the structure itself e.g. steel framework, metal backed plasterboard, facades etc
- Design of energy harvesting for harsh and hazardous environments
- Applications matrix for energy harvesting sensing systems and design tools, featuring case studies of successful practical implementation to encourage applications development and the building of a viable supply chain
- Hybrid energy harvesting technologies by combining sources, control and storage elements
- Design of multi-purpose energy harvesting components and infrastructure elements
- Energy harvesting from structural materials
- Improved impedance matching
- Development of MEMS energy harvesters in order to drive down their manufacturing costs
- Ultra-low power sensors
- Non-conventional circuits for low energy power conversion
- Step change in capability of energy storage components both in terms of capacity and speed of energy storage / delivery at a lower cost and with longer lifetime, possibly achieved using new materials with larger redox capacities that react more rapidly and reversibly with cations
- Software tools for optimising harvesters
- Optimising sampling/sleeping schemes for low energy budget measurements (spatially/temporally undersampled)

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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 second workshop in the series which was aimed at defining the research challenges in the area of energy harvesting to power structural monitoring sensor systems.

Energy harvesting technology is a key enabler in any drive to greater monitoring of the structural health of a range of types of fixed civil infrastructure where the use of batteries or mains power is either impractical or impossible. Energy harvesting would enable the powering of such sensor systems for the useful lifetime of the structure or the sensor system without the need for periodic intervention to change batteries. It would also enable embedded sensors to be included within the structure.

The Steering Board of the Energy Harvesting Network discussed a number of options for new and challenging areas of research and decided on energy harvesting for structural monitoring for this second workshop. This theme was judged appropriately ambitious in terms of research challenge and the challenging environment in which it must operate as well as offering an opportunity to bring completely new areas of expertise into the energy harvesting community.

The scope of this particular workshop included the powering of embedded and retrofitted sensors for structural monitoring on a range of types of fixed infrastructure. It primarily focused on applications that enable the automated monitoring of the health of these structures. Non-fixed structures such as airframes were out of scope. The workshop considered all approaches to energy harvesting possible, including those not currently viable.

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 involvement in research that enables this new generation of energy harvesting powered structural monitoring sensor. 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, electronics, wireless sensor networks, standards and energy storage as well as construction industry and structural health monitoring experience. 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 carrying out structural health monitoring, the power requirements of the sensing systems and the potential for energy harvesting solutions to address some of the shortcomings of other means of power. The facilitated workshop sessions then debated the specific technology developments expected to take place in the coming years and the science and engineering research challenges that will need to be addressed. This enabled the roadmaps 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 Steering Board and 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 roadmaps was 10 years from the present (until 2021) 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 the application of energy harvesting to power embedded and retrofitted structural health monitoring sensors on fixed civil infrastructure. Although there has been much recent interest in structural health monitoring, particularly in light of recent advances in wireless sensor networks, there has been very little focus on how energy harvesting might be a viable solution. There is thus very little practical experience to draw upon. Nevertheless, this exercise has drawn upon a very diverse group including the expertise of those who have delivered battery powered solutions for these environments and the collected experience of the UK energy harvesting community. It may have benefited from more involvement of construction industry specialists but these areas were covered by those who had indirect experience through having worked alongside such engineers.

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.

The scope of the application of energy harvesting extends to the powering of embedded and retrofitted sensors for structural monitoring on a range of types of fixed infrastructure. It primarily focused on applications that enable the automated monitoring of the health of these structures. Non-fixed structures such as airframes were out of scope.

The scope of the energy harvesting technologies applicable is taken as all approaches to energy harvesting possible, including those not currently viable.

Energy Harvesting to Power Structural Monitoring Sensors

Potential harvestable energy sources

Fixed civil infrastructure has a variety of forms and is present in a large range of environments. This infrastructure is essential to modern life, ranging from bridges and motorway systems to water treatment plants and energy-efficient buildings. This opens up a number of possibly harvestable energy sources. Some are already feasible for the powering of wireless sensing devices (e.g. solar) while others are feasible in principle but will require significant technical advances in order to make them feasible in practice e.g. adapting vibration-based methods to handle low frequency and/or irregular vibrations. Some possibilities are even further from realisation but are intriguing options for exploration e.g. the creative use of the whole buildings steel reinforcements to harvest the Earth's electromagnetic field or the exploitation of the galvanic protection already used on steel frames in structures, to electrochemically generate electric current.

Examples of sources:

- Displacement/flexing
- Thermal difference
- Vibration
- Solar
- Wind/air flow
- Various combinations of above in hybrid devices
- EMF
- Chemical processes

Vision

Robust and easy to install energy harvesting devices that can draw upon a range of ambient energy sources to aid the powering of embedded or retrofitted structural monitoring sensor systems for the appropriate lifetime of fixed civil infrastructure such as buildings, bridges, tunnels, dams, mines, pipelines, embankments, offshore oil platforms etc.

Drivers

Many of the drivers for the energy harvesting in this application are the drivers for the embedded or retrofitted structural monitoring sensing itself. The need for the sensors and the inconvenience of batteries or mains power is driving the need for the energy harvesting solution. The main drivers are economic, social, technical and policy and all are closely connected.

Economic drivers are dominated by various approaches to reduce the cost of construction and reduce the overall costs of ownership of structures in the longer term. They include:

- Reducing the costs of building infrastructure by reducing the degree of over specification through more detailed monitoring of actual loads, stresses and strains.
- Reducing the cost of owning and running buildings
- Reducing the compensation costs for injuries and deaths caused by damaged civil infrastructure (the typical cost per death is in the range of £1.4-2m)
- Changing business models of construction and servicing responsibility. This includes initiatives that could change the approach in the construction supply chain from the ‘physical delivery of a construction asset’ to a ‘model of service delivery’ where a full life cycle-oriented approach is therefore needed.
- Reducing build time by being able to better monitor settling / hardening of concrete
- Re-use of structures (e.g. foundation pilings or building frames) by enabling lifetime condition monitoring
- Predictive maintenance rather than repair to failure as well as easier forensic engineering in the case of failures
- Inadequate battery lifetime and reliability which results in expensive battery changes for retrofitted sensors and is impractical for embedded sensors – particularly impractical if sensing is to become ubiquitous
- Infrastructure built years ago where current loads were not anticipated – e.g. large numbers of bridges listed as structurally deficient but still in use
- Trend away from high cost inspection to lower cost ongoing monitoring using cheaper embedded sensors
- The negative impact (constraint) of rapid technology obsolescence whereby embedded, energy harvesting powered sensors would be superseded by better technology well before the useful lifetime of the structure was up thus encouraging a retrofit model and periodic intervention

Social drivers include:

- Increased expectation that buildings and other structures be designed for users’ convenience and welfare (accessibility, security, indoor air quality, etc.) with very significant consideration of safety, particularly with respect to natural forces e.g. earthquakes, storms etc.
- Increased desire for sustainable building solutions rather than knocking down and rebuilding so frequently
- Increasing resistance to proliferation of the use of batteries due to concerns about environmental sustainability
- The negative impact (constraint) of the conservative nature of the construction industry

Technology drivers include:

- Insufficient battery technology lifetime to enable embedded sensing despite continuous improvements to battery technology

- Advances in miniaturisation of devices, power management and reductions in the power requirements of sensing devices and communications protocols.
- Improvements in amount and efficiency of energy harvested
- Sufficiently mature wireless sensing devices that offer co-location of computational power with the sensing transducer
- Need to support autonomous execution of damage detection algorithms by wireless sensing devices
- Availability of hybrid harvesters
- The negative impact (constraint) of unproven (so far) reliability of EH over decades
- The negative impact (constraint) of improvements in battery technology that may address some lifetime and reliability issues
- The negative impact (constraint) of energy harvesting devices generally still needing energy storage devices that don’t last long enough for the intended applications. Further, present electrochemical systems rely largely on environmentally unacceptable materials.

Policy drivers and a proliferation of sustainability initiatives will mainly impact energy harvesting by affecting the acceptability of battery powered solutions and any efforts to extend the restrictions on use of heavy metals e.g. lead and bismuth. Drivers include:

- Increasingly common battery and waste management laws in Europe driven by efforts to reduce disposal in the environment
- Increased requirements to monitor structures for safety reasons
- Climate Change Act 2008 and its legally binding carbon emission reduction targets for 2020 and 2050 which will encourage greater efforts to find ways of reducing carbon emissions in the construction industry
- The negative impact (constraint) on energy harvesting of any efforts to extend the lead free directives to include PZT (found in piezoelectric energy harvesters)

Applications and Challenges

Currently we have a poor understanding of infrastructure during construction and after completion. This means we end up with a slow, wasteful and expensive industry. There is also a legacy of ageing infrastructure with typical lifetimes of 15-60 years but often used well past this. They are subjected to harsh loading scenarios and severe environmental conditions that are often not foreseen during the design and construction, resulting in long-term structural deterioration.

To address this structural health monitoring technologies can play a key role from cradle to grave reducing construction times and costs and ensuring safe use throughout a more clearly understood infrastructure lifetime. This forms part of an interdisciplinary technology solution that includes the latest sensor technologies and systems, data management tools, manufacturing processes, supply chain management processes and management of the built environment.

The extent of our ageing infrastructure is illustrated by a range of examples. London Underground has tunnels of 75-100 years old with deteriorating linings and minimal clearance between tunnel wall and trains. These are also at significant risk from nearby 3rd party construction. Thames Water has some 31,000 km of pipelines of which a half are more than 100 years old and a third more than 150 years old resulting in some 30% leakage in the system. There are also some 150,000 bridges in the UK forming critical links in the road and rail infrastructure and many of these have deteriorated and are below required strength for their current loads.

The requirements for structural monitoring systems will depend upon the application but these are typified by inaccessible locations with sensors operating wirelessly. Often sensors are positioned once a visual inspection has identified a concern. Inclinometers and crackmeters, for example, can be then be retro-fitted to the structure in order to provide long term monitoring of the situation by periodically wirelessly reporting any subsequent movement. Wireless Sensor Networks (WSNs) can be used to form a mesh network which is a flexible way of providing the required monitoring over large structures.

In existing deployments, each sensor node is powered using high capacity (e.g. 19 Ah) batteries. Sampling once every 3 minutes gives an average power consumption of 4.6 mW and a battery lifetime of over 500 days. Energy harvesting would be particularly useful to extend battery life or potentially power the systems directly (with a battery backup). The suitability of the different energy harvesting technologies (e.g. solar, thermal and vibration) will depend upon the application environment and the particular sources of energy available. For example, solar is not suitable for use in a London Underground tunnel but vibration and air-flow energy harvesters may be suitable. Harvesting from water pipes may be done by extracting energy from the water flow itself or by exploiting thermal gradients. Alternatively, bridges offer the potential for solar and vibration energy harvesting solutions.

The challenges for the energy harvesting technology are to supply sufficient energy, to be straightforward to install in inaccessible locations with minimal disturbance to the existing infrastructure and to be maintenance free for the required lifetime of the application. Future monitoring solutions are likely to require a systems level approach with a combined battery energy harvesting power source developed in parallel with integrated sensor and communications electronics to reduce the power consumption.

Technology development

Technology development, for the purposes of this roadmap, is taken as those relatively higher Technology Readiness Level (TRL) developments that are needed to enable the vision. They may be considered as those developments that will happen anyway for reasons not specifically connected to enabling energy harvesting powered devices, or that are not a major advance on the current state of the art. They are nevertheless needed to bridge the gap between the vision and what is currently possible.

This technology section summarises some of the main points from this part of the discussion. Full details of the workshop discussions are captured in the graphical representation of the roadmap (Appendix 2).

In the short term it is anticipated that solar energy harvesting will continue to be the most common type applicable for powering wireless monitoring sensors. Any improvements in this area will largely be in using smaller panels as enabled by reductions in power requirements with better electronic design. We are already seeing step changes in the power requirements of electronics and this is key in opening up the opportunities for energy harvesting. A systems approach is also becoming more common as power management issues continue to be a limiting factor in matching power needs to available harvested energy. In the coming year or so it is also likely that total cost models are likely to be developed to demonstrate to the construction industry the value of monitoring data. These will then more clearly outline the value of an energy harvesting powered or supported solution. Attention will also need to be paid to ensuring that the sensors devices and energy harvesting components are designed to be retrofitted and also periodically refreshed as the technology evolves and is updated. In this short term there is also a need for more work on determining the available harvestable energy in various structural monitoring scenarios.

In the medium term much of the effort will need to focus on bringing new energy harvesting technologies into practical use. These will include the eventual adoption of low cost MEMS harvesters and the development of low frequency vibration harvesters designed without significant increases in mass compared to the current technology. Broadband or wider band and non-resonant vibration harvesting is also anticipated to become practically feasible. New and lower cost materials are likely to be adopted in energy harvesting devices with work to be done on magnetostrictive materials which are able to provide DC from high force but low displacement applications. Lead free piezoelectric materials are also anticipated over this time frame thus overcoming some of the environmental concerns of the current PZT-based piezo devices. Further developments in control technologies will enable more efficient harvesting and storage. Reductions in the power requirements of standardised RF will also extend the potential of energy harvesting beyond the restrictions of the more bespoke low power communications standards. In this medium term it is also anticipated that the construction industry's influence will become stronger in this area. Changed infrastructure ownership models will drive appreciation of lifetime monitoring costs versus battery power cost and inconvenience. The industry will include retrofit capability into new building stock thus making use of energy harvesting powered sensors more widely and easily adoptable. Energy harvesting developers will start to supply solutions that are very much more plug and play and therefore easy for the construction industry to install.

In the longer term we will finally see the technology demonstrate proven longevity in harsh environments. It is also anticipated that some completely new approaches to energy harvesting will be developed and adopted that are built in to the structure during construction rather than needing retrofitting. Options include harvesting EMF from clever design of the steel reinforcement loops set in the concrete and exploiting processes like the galvanic sacrificial protection of steel infrastructure. By this time with pervasive wireless sensing the norm, structural health monitoring of civil infrastructure will be routine and therefore designed into the infrastructure itself.

Underpinning science needed

The underpinning science refers to the lower TRL science and engineering challenges that will not happen without a specific effort to focus resource here. This science and engineering addresses the gaps not covered above in relation to the vision for energy harvesting powering structural monitoring sensors.

The full details of the workshop discussions are captured in the graphical representation of the roadmap (Appendix 2). This underpinning science section summarises some of the main points from this part of the discussion.

In general, it is essential to establish the physical limits ('art of the possible') i.e. how much energy is available in the different contexts. This is essential because every civil infrastructure is different (unlike, for example, mass produced vehicles).

In the near term there will need to be significant focus on the development of a range of software tools. These include tools to enable accurate power prediction from site surveys in various structural monitoring scenarios and tools to enable the optimisation of the harvester's performance and the sensor node's use of the power. There are also further gains to be made in reducing the power needs of sensors by focussing on coming up with ultra-low power versions of the commercially available sensor techniques. Work is also required in the near term in the area of sensing strategies such as compressed sensing – the idea that more optimal sensing strategies can reduce the data transmission and hence power requirements. Programmes are also needed to start to develop the possibilities for combined sensor-energy harvester devices built in MEMS technology.

In the medium term it is anticipated that research will be needed to develop software tools that are able to synthesise optimum energy harvesting and power conditioning circuits. This will greatly speed up the design and development process as new energy harvesting techniques are developed. Work is needed to characterise the energy harvesting capability and long term resilience of new materials e.g. magnetostrictive materials which may have application for highly loaded energy harvesting. The area of impedance matching of the interface between an engineering structure and the energy harvesting device also needs investigation. Research is, for example, needed around the deployment of flexible materials and complex multi-materials systems, including: polymer and composite piezoelectrics for mechanical impedance matching in more flexible parts of structures; 2D technologies such as printed piezoelectrics and self-structured nanostructures (ZnO nanorods) and other additive technologies; piezoelectrics (and other devices) embedded into materials, single crystal and domain engineered piezoelectrics for micro and nanoscale devices. In addition, microfluidic approaches need investigation for microgeneration possibilities.

Although hybrid energy harvesting devices are already the subject of some research this tends to be the combination of currently accepted energy harvesting techniques. In the medium term there is also a need for research into other combinations to form hybrid harvesters e.g. the combination of standard energy harvesters with RFID approaches to enable more active RFID functions. The components and structure of a building itself also need to be examined for their ability to provide the energy to power the structural monitoring sensors e.g. thermal harvesting of server generated heat or local solar warming of structures or the harvesting of wind pressure on the large physical surfaces of buildings.

In the longer term there will be a need for new approaches to energy storage to overcome the limitations of batteries and supercapacitors. This may include electromechanical forms of energy storage or new ways to store heat. Research needs to be initiated to be able to deliver this. A further area of research required for the longer term is into energy transducers that may be able to convert one form of energy into another for easier or more efficient harvesting. For example, vibration or flexing may be best converted to heat energy for thermoelectric energy harvesting. As always, from the short term through to the very long term there will need to be continual research attention in the area of packaging for the harvesters, sensors and associated electronics.

Roadmap in graphical form

The roadmap with its sequence of layers for drivers, technology developments and underpinning science is presented in graphical form in Appendix 2.

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+):

- Integrated system design approaches for energy harvesting
- Harvesting energy from the structure itself e.g. steel framework, metal backed plasterboard, facades etc
- Design of energy harvesting for harsh and hazardous environments
- Applications matrix for energy harvesting sensing systems and design tools, featuring, case studies of successful practical implementation to encourage applications development and the building of a viable supply chain
- Hybrid energy harvesting technologies by combining sources, control and storage elements
- Design of multi-purpose energy harvesting components and infrastructure elements

EPSRC (TRL 1-3):

- Energy harvesting from structural materials
- Improved impedance matching
- Development of MEMS energy harvesters in order to drive down their manufacturing costs
- Ultra-low power sensors
- Non-conventional circuits for low energy power conversion
- Step change in energy storage components
- Software tools for optimising harvesters
- Optimising sampling/sleeping schemes for low energy budget measurements (spatially/temporally undersampled)

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

Skills, peoples, resources

In such a multidisciplinary area there is a clear need for new skills and the involvement of organisations beyond the existing energy harvesting community.

Development of new and improved devices will still require the involvement of the mechanical and electrical engineers who have for so long driven advances in energy harvesting technology. However, even in these areas new skills will need to be accessed. For example, there is an apparent increase in the need to interface new structural components and sensors. Sensor technology remains a huge challenge and a bottom-up approach is still needed. There is a great opportunity to learn from huge improvements in consumer electronics, particularly the smart phone industry, which has achieved radical improvements in power consumption.

Structural engineers develop appropriate combinations of steel, concrete, timber, plastic and new exotic materials. However, greater involvement of the materials community will also be required. Functional materials such as piezoelectric and magnetostrictive materials need further research and development to realise their potential in enabling energy harvesting. In addition, for the particular case of civil infrastructure monitoring devices powered by energy harvesting technology there will be a requirement for expertise in the area of construction materials for device encapsulation and ability to easily retrofit. Packaging/rigidity of the complete energy harvesting systems is extremely important as peripherals are known to suffer more than the electronic components. There are even issues related to reduction of opportunistic theft of components with good resale value such as solar panels or wind turbines. This requires new design approaches that combine security of the equipment with an emphasis on aesthetics and accessibility by the maintenance teams. It is recognised that some of these skills are hard to find in individual disciplines and curriculum changes may be necessary to provide them to the next generations of engineers involved.

The majority of the civil infrastructure monitoring devices will need to meet a range of national and international regulatory standards. The energy harvesting devices used to power them will need to be similarly compliant. To ensure that these energy harvesting devices are designed to comply there will need to be greater involvement of regulatory experts. There will also need to be significant involvement of civil engineers experienced in technology adoption and systems implementation so as to drive more widespread adoption by the industry.

The actual standardisation process in civil infrastructure is very fragmented and adapting very slowly to technological progress. There is a need to see how it could evolve more rapidly towards a set of standards integrating the various aspects of sustainable development including the benefit of new scientific and technical knowledge in energy harvesting. Where the standardisation process does not account for the use of innovative technologies, alternative paths should be explored e.g. by educating facility managers as to the performance and business development benefits of monitoring.

Aside from technical input there is also a need to be aware of legal (e.g. liability) and ethical issues and the wider impact of enabling monitoring of civil engineering infrastructure by energy harvesting. Engagement with a wider set of public and private stakeholders for input on needs, constraints and commercial or social viability is therefore essential. These stakeholders include the European Council of Civil Engineers (ECCE); public procurement agencies, insurance providers and of course the infrastructure users themselves.

Appendix 1: Workshop agenda

2nd Energy Harvesting Research Theme Workshop - Structural Monitoring
04 May 2011
TRW Conekt, Solihull

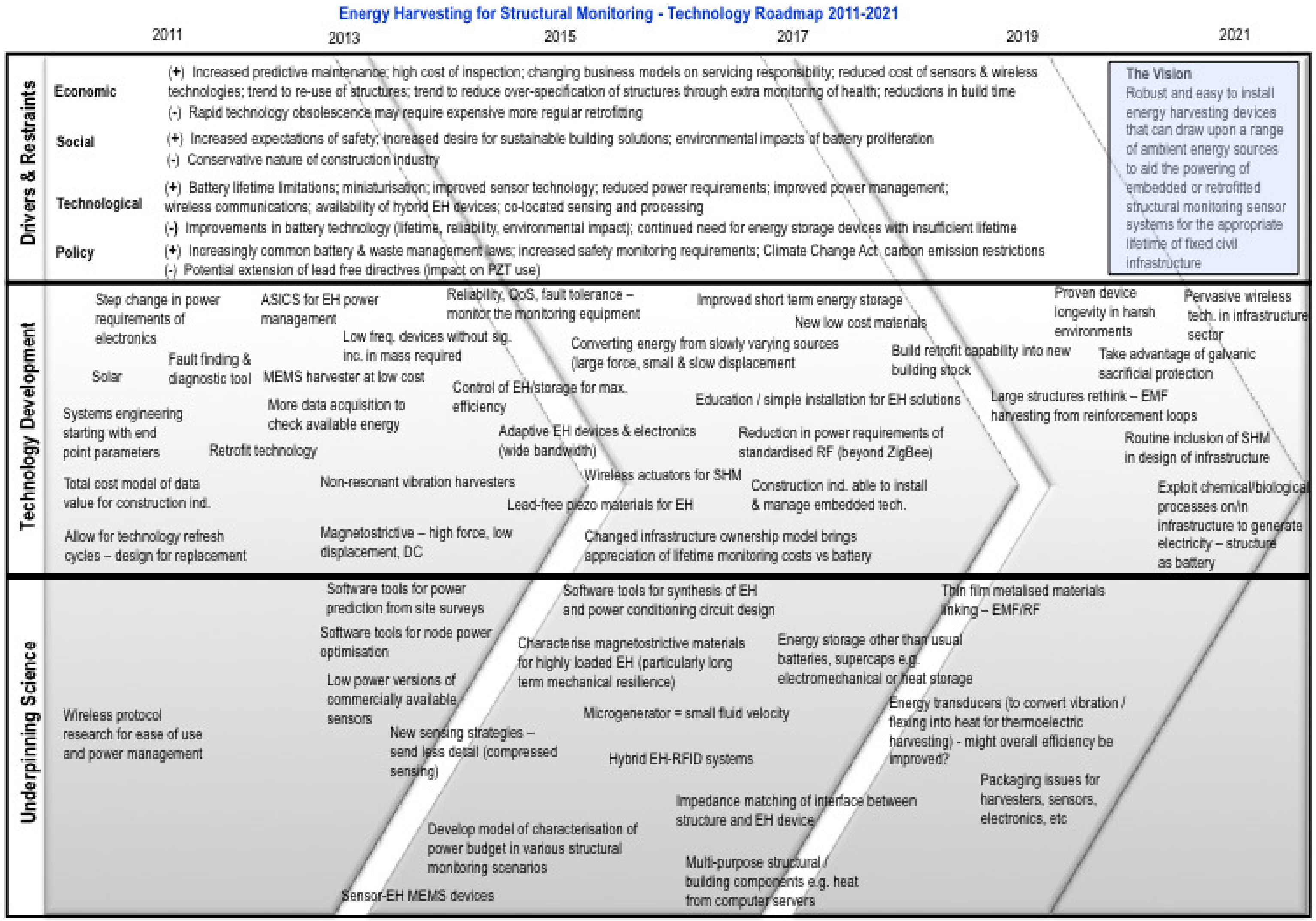
This workshop is designed to help facilitate the definition of a number of new research challenges and to catalyse the creation of multidisciplinary teams to address them. The agenda includes short presentations to get delegates thinking about the challenges of using energy harvesting to power the monitoring of structures such as buildings, bridges, tunnels and other fixed infrastructure. The facilitated workshop sessions will debate the specific technology developments and scientific advances that will be needed to realise the vision of these applications.

Agenda

9.30	Registration & coffee
10.00	Introduction - What are we trying to do and what is the process? *Roger Hazeldon, TRW Conekt*
10.10	Key Note Talk - Title to be Confirmed *Dr Kenichi Soga, University of Cambridge*
10.40	Roadmap Vision & Drivers *Simon Aliwell/Costis Kompis*
11:00	Coffee Break
11.20	The Design Issues and use of Wireless Energy Harvesting Devices for Maintenance Free Building Monitoring *John Corbett, EnOcean GmbH*
11.40	Facilitated Workshop - Technological Advances to Realise the Vision *Small Groups*
12:40	Lunch and Networking
13:40	SHM Demonstrator at NPL: Two Years of Monitoring Experience and Future Challenges *Elena Barton, National Physical Laboratory*
14.00	Addressing Power Requirements in Structural Monitoring Now and in the Future *Nick Baker, Adaptive Wireless*
14.20	Facilitated Workshop - Underpinning Science and Engineering to Realise the Vision *Small Groups*
15:50	Wrap up and Next Steps
16.00	Close

The workshop is by *invitation only* to ensure a high quality of interaction. To apply for an invitation, please email workshop@eh-network.org briefly saying what you would be able to bring to the discussion.

Appendix 2: Roadmap for energy harvesting enabled structural health monitoring



Energy Harvesting for Structural Monitoring - Technology Roadmap 2011-2021

Drivers & Restraints

Economic
(+) Increased predictive maintenance; high cost of inspection; changing business models on servicing responsibility; reduced cost of sensors & wireless technologies; trend to re-use of structures; trend to reduce over-specification of structures through extra monitoring of health; reductions in build time
(-) Rapid technology obsolescence may require expensive more regular retrofitting

Social
(+) Increased expectations of safety; increased desire for sustainable building solutions; environmental impacts of battery proliferation
(-) Conservative nature of construction industry

Technological
(+) Battery lifetime limitations; miniaturisation; improved sensor technology; reduced power requirements; improved power management; wireless communications; availability of hybrid EH devices; co-located sensing and processing
(-) Improvements in battery technology (lifetime, reliability, environmental impact); continued need for energy storage devices with insufficient lifetime

Policy
(+) Increasingly common battery & waste management laws; increased safety monitoring requirements; Climate Change Act, carbon emission restrictions
(-) Potential extension of lead free directives (impact on PZT use)

The Vision
Robust and easy to install energy harvesting devices that can draw upon a range of ambient energy sources to aid the powering of embedded or retrofitted structural monitoring sensor systems for the appropriate lifetime of fixed civil infrastructure

Technology Development

Step change in power requirements of electronics
Solar
Fault finding & diagnostic tool
Systems engineering starting with end point parameters
Retrofit technology
Total cost model of data value for construction ind.
Allow for technology refresh cycles – design for replacement
ASICS for EH power management
Low freq. devices without sig. inc. in mass required
MEMS harvester at low cost
More data acquisition to check available energy
Non-resonant vibration harvesters
Magnetostrictive – high force, low displacement, DC
Reliability, QoS, fault tolerance – monitor the monitoring equipment
Control of EH/storage for max. efficiency
Adaptive EH devices & electronics (wide bandwidth)
Lead-free piezo materials for EH
Wireless actuators for SHM
Converting energy from slowly varying sources (large force, small & slow displacement
Changed infrastructure ownership model brings appreciation of lifetime monitoring costs vs battery
Improved short term energy storage
New low cost materials
Education / simple installation for EH solutions
Reduction in power requirements of standardised RF (beyond ZigBee)
Construction ind. able to install & manage embedded tech.
Build retrofit capability into new building stock
Proven device longevity in harsh environments
Large structures rethink – EMF harvesting from reinforcement loops
Pervasive wireless tech. in infrastructure sector
Take advantage of galvanic sacrificial protection
Routine inclusion of SHM in design of infrastructure
Exploit chemical/biological processes on/in infrastructure to generate electricity – structure as battery

Underpinning Science

Wireless protocol research for ease of use and power management
Software tools for power prediction from site surveys
Software tools for node power optimisation
Low power versions of commercially available sensors
New sensing strategies – send less detail (compressed sensing)
Develop model of characterisation of power budget in various structural monitoring scenarios
Sensor-EH MEMS devices
Software tools for synthesis of EH and power conditioning circuit design
Characterise magnetostrictive materials for highly loaded EH (particularly long term mechanical resilience)
Microgenerator = small fluid velocity
Hybrid EH-RFID systems
Impedance matching of interface between structure and EH device
Multi-purpose structural / building components e.g. heat from computer servers
Energy storage other than usual batteries, supercaps e.g. electromechanical or heat storage
Thin film metalised materials inking – EMF/RF
Energy transducers (to convert vibration / flexing into heat for thermoelectric harvesting) - might overall efficiency be improved?
Packaging issues for harvesters, sensors, electronics, etc