Energy Harvesting
An EPSRC Funded Network

EPSRC
Engineering and Physical Sciences Research Council

Energy Harvesting from Human Power

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 first in a series of such exercises this study focuses specifically on energy harvesting from human sources for the purpose of enabling low power wireless sensing on, around and in the human body, while eliminating battery materials and waste.

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, materials, electronics, medical devices including implantables, wireless and body 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 battery-free human powered wireless sensing / monitoring devices.

Findings for energy harvesting outside the body were that technology development is needed in integration of different EH systems (e.g. PV/piezo/thermo)and in temporary storage circuits and devices for storing the harvested charge until it is supplied to power a system component. This may include solutions superior to the energy density and charging times provided by ultracapacitors. Other areas include low voltage and low frequency electronic design as well as data compression techniques. Proper integration of EH on and into body structures ought to receive attention as lack of it will limit usability and adoption. Major areas of underpinning science that will need to be addressed include materials, electronics (revival of analogue), communications technologies, and insights into complex aspects such as dietary and sleep.

Findings for energy harvesting inside of the body were that technology development is needed in a wide range of areas. This includes advances in mechanical designs, reductions in the power requirements of the medical devices, improved electronics and electronic design, traceable methods for measuring efficiency, demonstration of long term reliability and the development of advanced materials for a range of reasons including better biocompatibility and much improved efficiency of transduction. Major areas of underpinning science that will need to be addressed include materials, electronics, communications technologies, device construction techniques and harnessing the chemically powered potential of the body e.g. in implantable fuel cells using body fluids.

Research challenges that were identified from this roadmapping exercise include:

- Higher efficiency flexible thermoelectric structures that provide useful levels of electrical power from temperature gradients from 1 to 5 ^{o}C.
- The incorporation of energy harvesting functionality into compliant flexible materials and textiles so as to enable comfortable integration of the technology with minimal impact on the wearer.
- Compact adaptable inertial mechanical energy harvesters that are able to respond to excitations in the low frequency range (1 to 5 Hz). This approach will address multiple implant locations and applications where the harvester is mobile within the body.
- The development of fuel cells powered by body fluids.

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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 first workshop in the series which was aimed at defining the research challenges in the area of human power to support for example long-term health monitoring.

Energy harvesting technology is a key enabler in any drive to greater monitoring of the health of people that occurs outside of the clinical environment. Battery technology requires intervention by the patient or others and for implanted devices requires additional surgery. An energy harvesting solution could provide a fit and forget option for routine monitoring thus enabling the patient to experience much lower disruption to their quality of life.

The Steering Board of the Energy Harvesting Network discussed a number of options for new and challenging areas of research and decided on the human power topic for the first workshop. This theme was judged appropriately ambitious in terms of research challenge and also offered an opportunity to bring completely new areas of expertise into the energy harvesting community. The scope of this particular workshop on human power ranges from powering implantable medical devices to powering body worn devices and body sensor networks.

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) 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 human powered devices. 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, medical devices including implantables, wireless and body sensor networks, standards, energy storage etc. Whilst participants were primarily from the UK there was some representation from other European countries. The aim was to use the input of this group to define a vision and help develop a roadmap for achieving it.

The workshop agenda (see Appendix 1) included short presentations and panel discussions to get delegates thinking about the practical challenges of energy harvesting both inside and outside of the human body. The facilitated workshop sessions then debated the specific research challenges to be addressed and the expertise required thus enabling the roadmaps to be constructed.

The information gathered was validated through additional research and through further discussions with the Steering Board and identified experts.

The roadmap

The timelines and many of the research challenges for energy harvesting inside the body, e.g. for implantable medical devices, are different from those for energy harvesting for body worn devices and body sensor networks. It was therefore decided to construct two separate roadmaps and the workshop process was managed accordingly.

In building the roadmap the task and structure was broken down into the following:

- Definition of a vision
- 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
- Exploration of the skills, people and resources 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 human power in, on or near the human body. Although this is an area of considerable current interest, advances have been rather limited to date. Hence there is little direct 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 clinicians and designers but these areas were covered by those who had indirect experience here.

The scope of the application of energy harvesting extends to both powering of devices within and on or near the body. In the case of medical monitoring, differing needs will determine where the device is best placed and the energy harvesting solutions will need to be adaptable to this.

The scope of the energy harvesting technologies applicable is taken as any that draw upon the human body for the energy to be harvested. There has therefore not been a focus on bodily worn technologies that might harvest energy from other sources (e.g., solar energy, electromagnetic fields).

Energy Harvesting outside the body

Tapping directly into the biological processes that turn fat into energy is beyond currently available technology. However, energy might be harvested indirectly from everyday human actions or might be intentionally generated by a human. Indeed, products that operate in this mode, e.g. torches, radios, watches, have been on the market for years. At the same time, there has been a significant body of research on human generated power which can find potential applications particularly in low power biomedical applications. The related systems need to be wearable and typically consist of sensors, signal conditioning electronics and wireless transmission technology. More power allows longer operation, higher sampling rates, wireless transmission over a longer distance, and support of additional features. Therefore powerful, low weight and compact energy storage devices and energy harvesting from the human body are crucial technologies for extended and reliable operation.

Potential human power sources

Power may be recovered passively from body heat, breathing, blood pressure, arm motion, typing, and walking or actively through user actions such as winding or pedalling. In cases where the devices are not actively driven, only limited power can generally be harvested without inconveniencing or annoying the user. A summary of the potential power sources and the total power from various body-centred actions is provided in Figure 1.

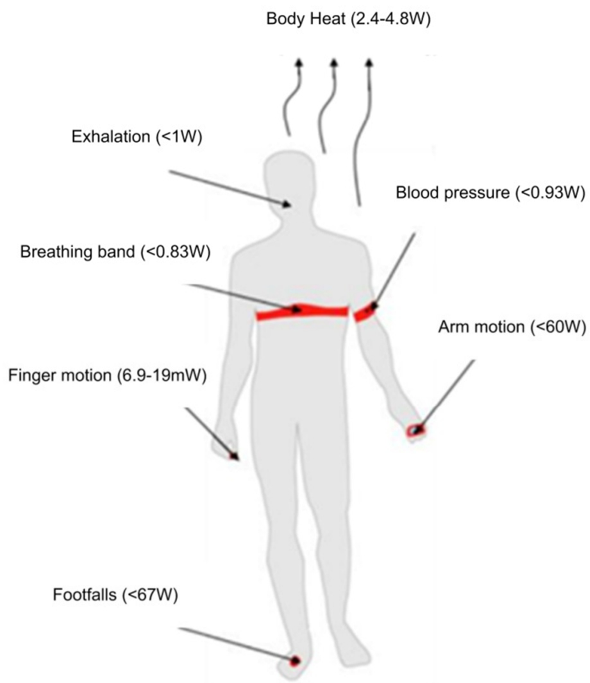


Figure 1 Possible power recovery from body-centred sources with total power for each action listed. Source[1]

Note, however, that energy harvested from the user may require considerable conditioning (storage, voltage/current or impedance conversion, etc.) before it can be

[1]Source: Starner, T., "Human Powered Wearable Computing", In IBM Systems Journal, Volume 35 (3), pp. 618-629, 1996.http://www.cc.gatech.edu/~thad/p/journal/human-powered-wearable-computing.pdf

used for an application. In fact, conversion efficiency remains a key challenge for scientists and technologies at present.

Vision

A wearable device able to generate power from passive human activity, that is integrated in everyday personal objects (e.g. clothes, watches, footwear, glasses) or attached on body parts and can remain unobtrusive to the user in terms of both use and maintenance.

Drivers

There are a number of drivers that will influence the likely development and take up of energy harvesting technology for outside the body type applications. These stem from economic, social, technical and policy factors and are all interrelated.

Economic

- Reduce costs for a given level of healthcare outcome.
- Provide independence for users, who don't have to worry about recharging batteries
- Provide independence for caregivers, who are increasingly employed

Social

- Need for improving mobility, reducing isolation and depression at all ages (which in turn impacts productivity, health costs and family well-being).
- Need for increased life-long independence. Includes supporting the ability to age in place (i.e., to enable the elderly to stay at home longer, happier and healthier).
- Contribute to prevention in areas of safety and monitoring to avoid medication errors and to monitor for falls, lack of activity, and other signs of physical or mental decline.
- Safety/privacy issues and concerns when using wearable devices (wireless attacks).

Technological

- Miniaturisation and developments in nanotechnology will play a significant role in wearable medical devices (e.g., lab-on-a-chip based diagnostics), making possible the use of harvested energy sources that are not currently viable.
- Advances in materials (e.g. lighter, stronger, compatible with EH component)
- Technology is merging with human anatomy and physiology to supplement or replace functions of cardiovascular, nervous, muscular, endocrine, visual, and auditory systems. This will in turn demand novel sources of energy.
- Power management techniques combined with new fabrication and device technologies are steadily decreasing the energy needed for electronics to perform useful functions, providing an increasingly relevant niche for energy harvesting in wearable systems

Policy

- Changes to healthcare working practice according to which Strategic Health Authorities will have a legal duty to promote innovation
- Changes to healthcare payment policy, e.g. payment by results, that will significantly alter procurement and reimbursement processes

- Regulations with regards to extend of clinical trials

Applications

Applications that would benefit from the ability to power the devices using energy harvested outside the human body would include on body monitoring, prosthetics and orthotics, and the recharging of secondary batteries for portable electronic systems.

On body monitoring applications cover health, rehabilitation and care; personal and home safety and security; personal activity management; biorobotic systems; and person-centred services. Other applications target tele-monitoring and self-management of chronic diseases; tele-monitoring of health parameters using wearable and/or implantable multisensor platforms.

Prosthetics and orthotics combines knowledge and understanding of the human body with the application of forces and evaluation of mechanical components. Targeted body parts may include hip, knee, ankle; shoulder, elbow and hand.

Portable electronic systems include any autonomous device that is powered by a battery. The battery can be augmented by energy harvesting with secondary batteries being recharged from energy harvested outside the human body. As these devices are mainly at the research stage, many improvements will be needed concerning all their parameters. We expect that this will mainly be driven by military or space applications where cost is not a primary concern and not by assisted living applications.

Clinical power requirements for control and actuation are significant so as to address general clinical requirements such as oxygenation, dynamic interface pressure and shear, motion tracking, activity monitoring, bone movement, temperature. Promising energy harvesting opportunities include both thermal (body device interfacing thermal differential) and kinetic energy (flexion & extension of components – hydraulic control units, structural deformation, shock absorption/dissipation).

Technology development

Electrical energy can be harvested from outside the human body by employing a range of different transducers including thermoelectric devices, piezoelectric materials, variable capacitors, and inductive generators. For example, thermoelectric generators take advantage of differences in temperature between the device wearer's body and the air to induce heat to migrate to the cooler region of a thermoelectric system. This heat flow carries electrons with it, thereby generating a current. Today's thermoelectric generators operate when a temperature difference of greater than 10^{o}C exists and can provide sufficient energy to power a useful function (e.g. to feed a pulse oximeter). A key research goal is to reduce this minimum temperature difference requirement.

Digital circuits use more energy than optimised analogue circuits to accomplish the same calculations and signal processing tasks, thus producing more heat. Thus, in the context of developing human powered devices, good analogue electronic design is a key competence. Furthermore, analogue systems have reduced heat dissipation in the tissue surrounding them and manage the circuit noise better.

Another area of technology development is flexible electronics – a technology for assembling electronic circuits by mounting electronic devices on flexible plastic substrates, such as polyimide. In addition, power-generating rubber films exist and can take advantage of natural body movements such as breathing and walking.

Smart fabrics and interactive textiles may also drive the development of EH technologies. These textiles are able to sense stimuli from the environment and react or adapt to them in a predetermined way. For example, smart textiles/garments can incorporate sensors/actuators, processing communications, and user interfaces.

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.

The full details of the workshop discussions are captured in the graphical representation of the roadmap referred to below. This underpinning science section summarises some of the main points from this part of the discussion.

In the short to medium term motion-driven and thermoelectric devices are likely to be the main types of energy harvesting devices outside the body. For motion movements key areas include nano and micro-scale structures / composites.

Another area where scientific research may underpin EH outside the human body is concerned with understanding the dietary aspects – food management that produces more energy but also the purposes and mechanisms of sleep which are only partially clear. Sleep is often thought to help conserve energy, but in fact the metabolism of the human body only reduces by about 5–10%. Valuable knowledge may be extracted by studying power generation in unusual environments such as the deep oceans where organisms are known to be able to generate power even from poisonous gases.

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 has highlighted the following research challenges:

- Higher efficiency flexible thermoelectric structures are needed that can provide useful levels of electrical power from temperature differentials in the range 1 to 5 ^{o}C.
- The design of mechanical energy harvesters will be vary depending upon the location on the body. A research challenge is therefore to develop unobtrusive mechanical energy harvesters designed specifically for key locations such as the foot, lower leg, knee, chest and arm.
- The incorporation of energy harvesting functionality into compliant flexible materials and textiles so as to enable comfortable integration of the technology with minimal impact on the wearer.
- Compliant and flexible energy storage devices, power conditioning electronics and sensors to provide, in conjunction with the previous challenge, fully integrated self-powered sensor systems for body area networks

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

Energy Harvesting inside the body

Potential human power sources

Within the body, the most obvious potential power sources involve harvesting energy from movement (kinetic). Kinetic harvesting for most implantable sensing devices would likely be inertial devices where the limits are due to size of the displacement mass and positioning within the body for maximum displacement during motion. Non-inertial devices are a possibility in some cases but do raise the issue of very invasive surgery to attach to the expanding / moving body part. Surgically it may be preferable to carry out periodic battery replacement for many applications. Nevertheless, there are proposed solutions that could involve attaching nanowires or piezoelectric materials to flexing organs.

Further potential may be found in human bodily fluid powered micro fuel cells although this would present issues of hermetically sealing the device since it will need to rely on the body to produce the chemicals required for the fuel cell.

Although not strictly energy harvesting from the ambient environment, the use inductive coupling to power implanted devices will continue to be the focus of attention for some applications to recharge internal storage devices or where sensing is not required continually.

Vision

The vision defined through the workshop is to develop:

A revolutionary bio-compatible implantable energy harvesting device able to convert the energy source into electrical power over its lifetime within the patient.

The harvester should deliver sufficient power for the application whilst maintaining a form compatible with existing surgical procedures and being entirely transparent to the patient.

Drivers

There are a number of drivers that affect the likely development and take up of energy harvesting technology for medical and health type applications.The main drivers are economic, social, technical and policy and all are closely connected.

Economic drivers are dominated by a need to contain the cost of healthcare given the increasing burden on public fincances of an ageing population with its expectations of improved quality of life. In addition, there is an increased need to monitor conditions that are becoming more common as a result of modern lifestyles (e.g., diabetes, obesity). The results are trends towards earlier diagnosis to minimise referrals and ensure better disease management (preferably at point of care) and an increasing level of care in the home or community. This is likely to be supported by an increased level of self-monitoring and the involvement of the retail sector in supplying monitoring devices and services. The increase in adoption of Assisted Living technologies and solutions is further evidence of this. For many people, earlier monitoring may be the key to preventative healthcare, enabling behavioural changes and avoidance of costly treatment at a later stage. For those needing follow-up monitoring after operations, the use of wireless, implantable devices will provide a cheaper and more convenient way to gather more frequent data and therefore manage and minimise the risk of needing readmission.

Social drivers include the ageing population which creates a greater demand for ways to manage and improve quality of life whilst living with chronic long term conditions. In addition, there is a trend towards greater patient empowerment – more involvement of the patient in the management of the condition and more choices to be made. An increased concern for patient safety could also drive the adoption of more regular monitoring either for management of conditions or for better and more convenient post-operative monitoring. Running counter to this is a likely concern about data privacy, a reluctance by some to interact with technology and a resistance to reduced personal interaction (e.g., with healthcare professionals).

Technology drivers include the increasing potential to monitor vital signs and specific medical conditions using low cost sensors. This is aided by advances in miniaturisation of devices, power management and reductions in the power requirements of sensing devices and communications protocols. In addition, the powering of such devices is enabled by both improvements to battery technology and the emergence of energy harvesting technologies as a means to support 'fit and forget' rather than invasive procedures for regular battery changes. Advances in biocompatibility of materials and the increased development of implantable devices, including both monitoring and drug delivery, is opening the way for further opportunities for energy harvesting to power devices within the body. Development of monitoring devices for sport use will also help drive the technology for wider health applications. With the increased use of MRI within the hospital setting for both diagnosis and ongoing monitoring of treatment, there will be a drive towards greater MRI compatibility of medical devices, particularly in the materials used and device packaging.

Policy drivers will mainly impact energy harvesting by their ability to change healthcare approaches. In the UK, National Service Frameworks have targeted improvement in specific areas, many of which lend themselves to greater use of monitoring devices e.g. diabetes, heart disease, stroke rehabilitation, care for the elderly etc. In addition, the change to Payment by Results will open up opportunities for alternative approaches and healthcare pathways. Sustainability arguments and eventually legislation are likely to drive a greater focus on avoiding the proliferation of batteries due to the problems of disposal. A possible future demand for 'lead free' in medical devices would also impact on both batteries and some types of energy harvesting devices. A restraint on future uptake of energy harvesting to power implantable devices may be increasingly complex processes for regulatory approval.

Applications

Applications that would benefit from the ability to power the devices using energy harvested inside the human body would include both implantable devices and swallowable devices. Non-human bodies (e.g. livestock) will provide both a less regulatory burdened route to the early development and testing of devices and some interesting niche applications in their own right.

Current swallowable devices are designed for relatively rapid transit through the digestive system so battery power is sufficient. Future potential applications requiring longer residence time within the body e.g. swallowable cameras that require motor control for navigation may well require energy harvesting solutions.

Implantable devices require surgical insertion so where possible the avoidance of batteries, which require further surgical intervention for changing, is desirable. Implantable devices may include sensing devices under the skin monitoring indicators in the blood. They may also include sensing devices implanted within artificial joints to monitor wear and within transplanted or repaired organs to monitor vital functions. Subcutaneous drug delivery systems may also require power to release based upon measured levels.

Looking far into the future it could be imagined that devices able to navigate blood vessels and relay back sensed data might need powering using energy harvesting techniques.

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 implantable 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 3).

In the short term it is anticipated that technology advances will deal with the need to develop mechanical designs that can harvest energy from lower frequency vibrations, thus widening the applications scenarios. It is also anticipated that significant advances will be made in reducing the power requirements of the devices (both the medical devices and the energy harvesting devices within them). This trend will continue into the medium term, broadening the range of devices that can potentially be powered by energy harvesting. Some of these advances will come through improvements to the electronics and electronic design in the short to medium term but in the longer term is likely to migrate towards non-silicon electronics.

A combined sensor and energy harvester is expected in the relatively short term and its development and implementation should address some of the integration and optimisation issues inherent in developing energy harvesting powered devices.

Performance characterisation and comparison will be greatly helped by the development of traceable and accurate methods for measuring efficiency of energy harvesting materials and devices. In the medium term we will also reach a point where the reliability of energy harvesting devices over significant numbers of years to perhaps a decade will have been practically demonstrated thus encouraging more widespread acceptance.

There is a strong materials theme running through the short, medium and longer term. Biocompatibility of electronics will be addressed, piezoelectric materials will gain general acceptance as a viable approach and efforts will be made to resolve the issues of coupling energy harvesting devices to biological tissues with very low losses. In the long term better device-body compatibility will be enabled by ‘soft’ construction of the devices from suitably compatible materials. New materials will also emerge in the medium term that enable energy transduction with >50% efficiency. It is also anticipated that in the longer term new materials enabling new transduction methods will emerge. By the medium to longer term it is expected that legislation on the use of rare earth metals and heavy metals will have an impact, probably acting to promote compatible energy harvesting technologies as a sustainable replacement for batteries.

A medium to longer-term advance will be the emergence of power sources that exploit the body’s own fluids or systems. To start with this will probably involve fuel cells powered by body fluids (e.g. urine) but in the longer term could possibly exploit energy stored in food or alcohol.

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 devices inside the human body.

The full details of the workshop discussions are captured in the graphical representation of the roadmap (Appendix 3). This underpinning science section summarises some of the main points from this part of the discussion.

Materials aspects will clearly need to be addressed in scientific and engineering research for many years to come if the technology advances are to be realised. There will need to be research into magnetostrictive materials to see how they might compare to piezoelectric materials for energy harvesting in the short to medium term. Research into new materials with ultrahigh energy density and new biocompatible materials will also be needed on a similar timescale. Nano and micro-scale structures and composites will be researched for applicability to energy harvesting. In the longer term, polymer materials with high dielectric constants will need to be examined for potential.

The focus on electronics is repeated here in the underpinning science section with the research focus being on related challenges. These include, in the shorter term further exploration in the field of room temperature superconductivity. In the short to medium term there is a clear need for research addressing the area of power conversion circuitry that is efficient at low voltage and able to handle conversion with non-periodic stimuli. In addition in the medium to longer term there was much interest in research to develop new ways of rectification from the present limit of a few hundred millivolts down to zero via novel electronics. In the longer term it is anticipated that research will turn to biologically based circuitry which may even lead to neuron integration into the implantable device.

As with the technology development section, harnessing the chemically powered potential of the body is thought to hold much research potential. In fact some of the points made previously may be better positioned within this underpinning science section. There is a need, in the medium to long term for research into accessing the body’s natural energy storage (ATP) and coupling this to non-biological energy storage for the powering of an implantable device. In the long term this may lead to research into bio-inspired chemical fuel cells with neural electrical circuits. It is likely to also require further research into biocatalytic materials and processes and a better understanding of biofouling agents and their growth.

Research into the communications aspects relevant to future implantable, energy harvesting powered, medical devices is also required. Any developments that can offer the potential to send more data for less energy (i.e. moving closer to the Shannon capacity) would be valuable enablers. This is expected in the relatively short term. In the medium to longer term there should also be research into nano-antennae to enable ultra small scale devices.

Device construction is another area of research focus over the period examined. In the short term it is felt that standards and terminology are required to facilitate better comparison of the results of research efforts. In the medium term research will be needed into sub-mm to micron scale manufacturing techniques to enable processes to eventually be developed to deliver the devices required for implantable applications. Research into a self powered lab-on-a-chip is also required in the medium term. Systems level research is an area requiring much attention in the medium term. Self assembly of, for example, ZnO nanowires is a theme of research for the medium to longer term to enable practical delivery of energy harvesting devices into the body. Over the same time frame it is also anticipated that there will need to be research into self-tuning energy harvesting generators.

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 3.

Key research challenges

The exercise to build the roadmap has highlighted the following research challenges:

- Compact adaptable inertial mechanical energy harvesters that are able to respond to excitations in the low frequency range (1 to 5 Hz). This approach will address multiple implant locations and applications where the harvester can be placed in various places within the body.
- Flexible, biocompatible energy harvesting materials that can used in specifically designed harvesters, or be built into in-vivo devices and instruments that harvest energy from forces and movements within the human body. The energy harvesting material may also be used as the sensor element depending upon the application.
- The development of fuel cells powered by body fluids.

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 for analogue electronics expertise driven by the need to use less energy and interface new power supplies and sensors.

Greater involvement of the materials community will also be required. Functional materials such as piezoelectric and magnetostrictive materials need further research and development to realize their potential in enabling energy harvesting. In addition, for the particular case of implanted medical monitoring devices powered by energy harvesting technology there will be a requirement for expertise in the area of biocompatible materials for device encapsulation and probably biocompatible electronics.

Whether body worn or implantable, any medical monitoring device 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 clinicians able to bring specific applications knowledge and experience at taking technology through clinical trials.

For many of the body worn, body sensor networks and prosthetics and orthotics applications, expertise that is likely to be required includes physiology, gait analysis and design in general to address issues of comfort, aesthetics and functionality.

Aside from technical input there is also a need to engage with a wider set of stakeholders for input on needs, constraints and commercial or social viability. These stakeholders include the National Health Service, Department for Health, regulators (e.g. water when washing intelligent clothing); charities (e.g. Age UK, Wellcome Trust); insurance providers and of course the patients and taxpayers.

Appendix 1: Workshop agenda

1st Energy Harvesting Research Theme Workshop
9 November 2010
Imperial College London

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 energy harvesting both outside and inside the human body. The facilitated workshop sessions will then debate the specific research challenges to be addressed and the expertise required.

Agenda

9.30	Registration & coffee
10.00	Introduction
10.05	State of the Art in Human Powering of Devices *Prof Markys Cain, NPL*

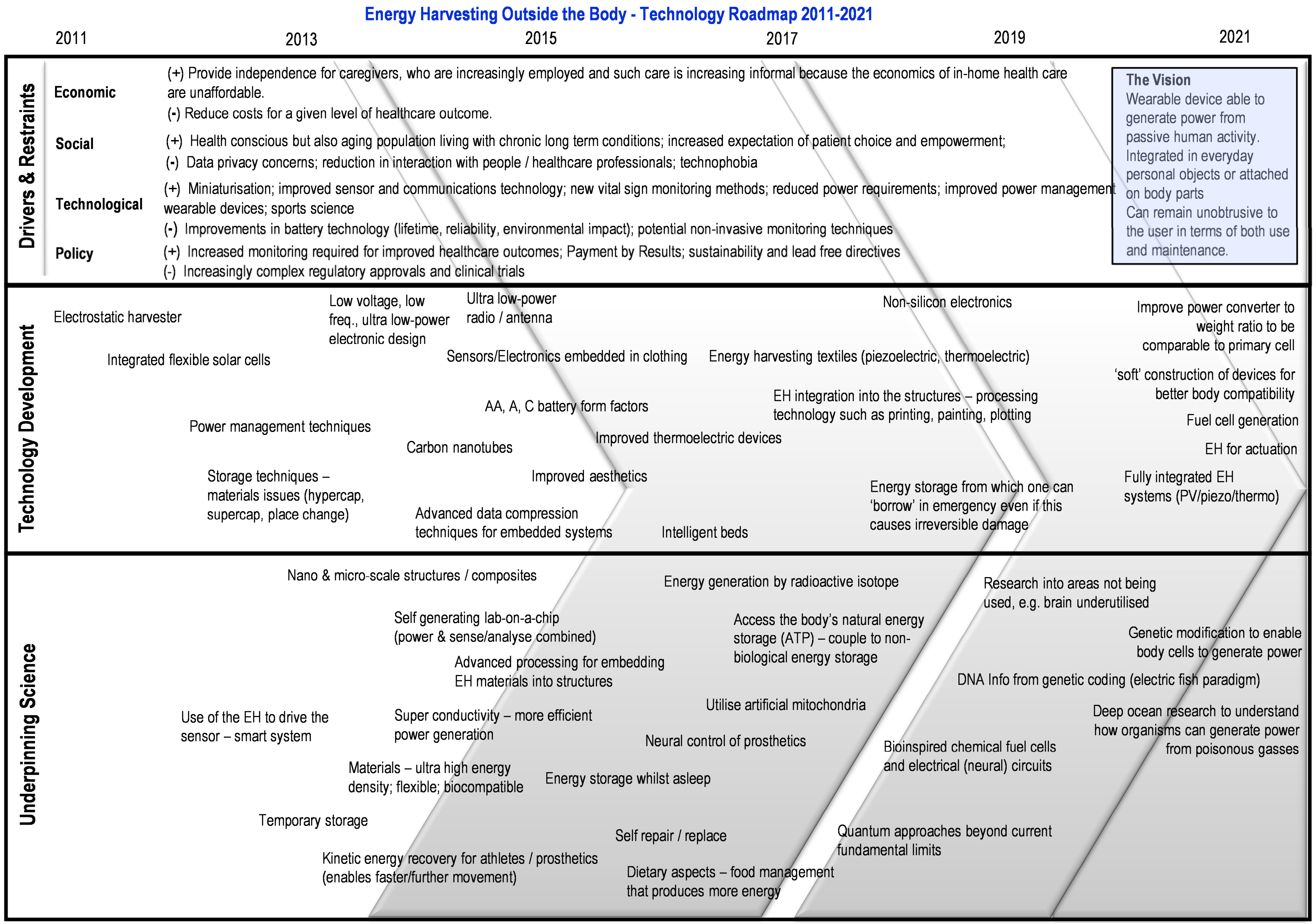
Session 1: Aspects of Human Powering of Devices Outside of the Body

10.35	Energy Requirements for Prosthetic and Orthotic Devices in Research and Clinical Applications *Dr Arjan Buis, University of Strathclyde*
10.50	Energy Harvesting in Prosthetic Legs using Piezoelectric Materials *Dr Kesorn Pechrach Weaver, Ronsek Ltd.*
11.05	Q&A and General Discussion
11.25	Coffee break
11.50	Facilitated Workshop
13.00	Lunch and networking

Session 2: Aspects of Human Powering of Devices Inside of the Body

14.00	Power from a Heartbeat *Tracy Wotherspoon, Zarlink Semiconductor*
14.15	Application of Human Power for Pervasive Sensing in Sports and Healthcare *Dr Benny Lo, Imperial College London*
14.30	Q&A and General Discussion
14.50	Coffee break
15.05	Facilitated Workshop
16.10	Wrap up and Next Steps
16.15	Close

Appendix 2: Graphical representation of roadmap for energy harvesting outside the body



Appendix 3: Graphical representation of roadmap for energy harvesting inside the body