Final Publishable JRP Summary for ENG02 Harvesting
Metrology for Energy Harvesting

Overview

Energy harvesting is the generation of small scale energy from ambient sources such as movement, vibration or waste heat, either in the environment or resulting from human activity. It provides high value energy at the point of use that can be used to power electronic devices indefinitely, free from wires and/or batteries. Applications include industrial monitoring, medical implants, "smart" energy distribution, traffic and asset control, and wearable electronics. By recycling energy such as waste heat from vehicle exhausts, energy harvesting can also improve efficiency, reducing fuel consumption in cars by 5-10 %.

This project developed European metrology capability to support the commercial development of energy market, including support for emerging new technologies at the micro- and nano-scales.

Need for the project

Our modern technological society relies increasingly on the massively widespread use of low power devices for communications and information technology. The proliferation of portable electronic devices has seen massive growth in wireless technologies, set to grow exponentially as a wider range of devices become connected (the Internet of Things). Providing power to wireless devices presents a significant challenge that could be addressed with the harvesting of ambient sources of energy. This could eliminate the need for wired power connections or expensive and polluting batteries in many applications (an energy harvester, operating for a lifetime of 20 years would generate the energy contained in roughly 70 standard primary button cells). On a larger scale, improved efficiency through waste heat harvesting could make significant reductions in energy usage, and CO_2 emissions, particularly in the automotive sector.

European industry, supported by investment in research and development, has made strong growth in energy harvesting for industrial monitoring and building controls. However, there is unrealised potential for energy harvesting to achieve wider mass-market adoption (estimated to be worth €5 billion by 2022). A major reason for this is uncertainty over performance expectations within the supply chain. Therefore, development of agreed metrics, reliable methods for their measurement and their incorporation into standards are required in order to accelerate market adoption of energy harvesting technology. This metrological development needs to embrace emerging new technologies that will provide energy sources at the micro and nanoscale, as well as industrial scale energy harvesting.

Scientific and technical objectives

The overall scientific and technological objective of the project was to provide, within Europe, the metrological framework, technical capability, and scientific knowledge to enable the development of effective and commercially successful energy harvesting technologies. This ranges from the use of known technology in novel ways, to the development of new technologies and materials to meet the growing market demand for energy harvesting. This project addressed three main challenges in energy harvesting metrology:

1. Power from energy harvesting is usually on a small scale and is intermittent in nature. The signals from energy harvesters are not clean sine waves that we can measure very accurately but they are noisy signals of varying profiles. Thus, existing measurement techniques are not adequate for measuring the weak and distorted signals generated by most energy harvesters. There is also a lack of agreed definitions and metrics of terms such as efficiency, effectiveness or power output that can lead to confusion in the market.

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2. There are challenges relating to particular energy harvesting technologies. For vibrational or motion energy harvesting, there are no agreed methods for specifying performance parameters (efficiency, power, power density) or their measurement, leading to widely varying reported metrics that have little bearing on what could be achieved in practice. The measurement of the performance of thermoelectric converters for waste heat recovery is also subject to very large measurement uncertainties, and a lack of reference materials, particularly at elevated temperatures.
3. There is a drive to develop ever smaller energy harvesting devices that can be integrated with the electronics they are powering, and to exploit emerging new nano-technologies for energy harvesting. This requires the development of suitable techniques for performance characterisation at the nano-scale. By providing robust traceable measurement for emerging new materials and energy conversion technologies, this will help accelerate the development of new products, new applications, and new commercial opportunities for energy harvesting

To address these three main challenges this project had the following aims:

- To develop the metrology framework to provide traceable and reliable measurement of thermal, mechanical and electrical properties that relate to the transduction of thermal or vibrational energy into useful electrical quantities.
  - For vibration and motion harvesting this requires the capability to reliably and traceably map performance under varying conditions encountered in practical situations (performance mapping).
  - For thermoelectric harvesting, new techniques are required to provide more accurate measurements and reference materials for industry, particularly at elevated temperature.
- To develop measurement definitions and techniques for the characterisation of efficiency and power output in energy harvesters, allowing industry to compare technologies and techniques.
- To develop traceable techniques for the measurement of small AC and DC electrical quantities with complex waveforms typical of energy harvesting applications.
- To establish measurement techniques for the characterisation of thermal and mechanical energy transduction at the micro- and nano- scales.

Results

This project focused on thermal and electro-mechanical conversion. For thermal converters, the technology of most interest, commercially and in research, is thermoelectric conversion. For electro-mechanical conversion, we adopted some generic approaches to measurement at different lengthscales through the simultaneous characterisation of electrical and mechanical quantities. We also addressed technology-specific issues relating to energy converters that are of major interest commercially and under research, specifically piezoelectric, magnetostrictive and electrostatic energy harvesters. Key project outputs were:

Performance mapping of vibrational energy harvesters

Energy harvesting output depends on the amplitude and frequency of the vibration source as well as the load circuit. New facilities were developed to perform sophisticated performance mapping of vibrational energy harvesters with parametric variation of frequency, acceleration and load resistance. In many situations the power output does not scale linearly with vibration amplitude, so this kind of performance mapping will provide important input into the development of standardised test methods and performance metrics. Unique new facilities were also created for performance measurement of magnetostrictive energy harvesting technology for applications such as power harvesting engine mounts.

New high temperature reference samples for thermoelectric converters

The industrial realisation of accurate measurement of thermoelectric converter performance demands the availability of well-characterised reference materials. However, there is a lack of reference materials for the high temperature measurements required by the automotive industry. Two reference materials for Seebeck coefficients were characterised in the temperature range between 300 K and 650 K (Bi-PbTe) and between 300 K and 860 K (ISOTAN®). The relative measurement uncertainties ($k = 2$) obtained of the Seebeck coefficients were in the order of only a few percent, and it is the first time that reliable reference materials for Seebeck coefficients with low uncertainties at temperatures above about 400 K have been made available.

Reduced uncertainties of measurement for thermoelectric converters.

Large uncertainties are associated with the measurement of thermoelectric harvesting, largely resulting from measurement of thermal properties, particularly at high temperature. New facilities have been designed and constructed for measuring the thermal conductivity of thermoelectric materials from room temperature to 725 K resulting in reductions in relative measurement uncertainty to between 5 % and 8 % (k=2).

Efficiency measurement in vibrational energy harvesting

For thermo-electric converters, efficiency is well defined (although difficult to measure). However, this is not true for electro-mechanical energy conversion, which requires a measurement of the mechanical energy input to a device as well as the electrical output. This project set up unique facilities for the measurement of efficiency for electromechanical conversion, and developed models to predict efficiency in examples of commercial interest such as the piezoelectric cantilever. Efficiency is closely related to loss, and novel work within the project identified new sources of internal loss in piezoelectric converters, and demonstrated that power output can be significantly improved by reducing the amount of piezoelectric material, potentially saving cost as well as improving performance.

Traceable measurement of electrical quantities

The ability to traceably measure electrical power is central to the metrology of energy harvesting. This project developed new techniques for power measurement for the complex signals typically encountered in energy harvesting power measurements. These complex waveforms contain a wide range of frequencies, and to achieve accurate, traceable measurement requires detailed knowledge of the instrumentation characteristics. This project developed a new waveform generator that is able to precisely mimic over a million different waveforms or shapes of the kind that are produced by energy harvesters. Because the properties of these simulated waveforms were already known, we were then able to use them to test and calibrate measurement equipment.

Energy harvesting at the micro- scale

Micro-Electro-Mechanical-Systems (MEMS) technology is an important developing area for energy harvesting. This project developed a suite of measurement facilities to support the development of MEMS energy harvesters. Energy conversion in MEMS devices is critically dependent on the often complex mechanical response to vibration, and damping from air movement and internal losses. This project developed a miniaturised vibration source integrated with a Laser Doppler Vibrometer scanning microscope to relate mechanical response at the micro-scale to power output for MEMS devices. A new technique was also developed for characterising the mechanical properties of MEMS harvesters by electrical measurements alone. Validation of measurement techniques requires performing measurements on well characterised devices, so piezoelectric and electrostatic MEMS samples were built to our own designs.

Energy conversion at the nano- scale

Atomic-force microscope techniques were applied to the traceable measurement of energy coupling and electrical and thermal properties at the nanoscale. These techniques will pave the way for reliable measurement of energy conversion in emerging new nanostructured thermoelectric and piezoelectric energy harvesters.

Actual and potential impact

Dissemination:

- The project generated over 50 media articles in publications including the Smithsonian Magazine, Electronics Weekly, The Engineer, European Energy Review, Wind Energy Network, Pan-European Networks: Science & Technology, The Telegraph, as well as appearances and interviews on the BBC TV and the World Service radio. In addition, 11 scientific papers were published in high profile journals, including Applied Physics Letters and Energy and Environmental Science.
- 11 editions of the “Metrology for Energy Harvesting” newsletter were distributed. Each issue included project news and a “view from industry” interviews with industry leaders working in the field. The newsletter was circulated to the project stakeholder group (over 100 contacts, 59% are from industry), and was available to download from the project website.
- An end of project dissemination event provided an overview of the project achievements and workshops to an audience of industry and research organisations. The event was also webcast, and webcast recordings are available from the project website.

- This project developed industrial training courses which were delivered in collaboration with IDTechEx as part of their Masterclass workshops at industry focussed conferences on energy harvesting and wireless sensors.

Standards:

- ISA100.18 (International Society of Automation) power sources standards committee requested work on the development of standardisation of performance metrics and measurement techniques. It is envisaged that eventual adoption as an IEC standard will be sought.
- Discussions were held with the secretary of IEC/TC 113 'Nanotechnology standardization for electrical and electronics products and systems' on the development of measurement standards of piezoelectric and thermoelectric energy harvesting and energy storage using nano-structured materials, as well as identifying a potential need for nanoscale characterisation of functional properties.
- Discussions were held with the chair of IEC TC47 who started developing energy harvesting standards, regarding representation of our energy harvesting work on this committee. The project will seek to participate in future development of these standards.
- A report on standardisation activities in energy harvesting was published as an industry report by the UK Knowledge Transfer Network (KTN) Energy Harvesting Special Interest Group.

Industry Impact:

- Morgan Advanced Materials, a global materials engineering company, supplied NPL with a variety of components for producing standardised energy metrics, which the market can understand. This will help to define and characterise the product range and provide potential customers with a clear understanding of the output of a device in their environment.
- The project also worked with a FTSE 100 global engineering company to apply the measurement facilities developed to energy harvesters under development by the company.
- Piezoselex "Piezoelectric Pair Materials for the Selective Exclusion of Workplace Noise" is a Research for SME's, European Seventh Framework project for the development of an improved device for the prevention of noise induced hearing loss. The innovative new solution allows specific ranges of sound frequencies (i.e. those within the range of speech and alarms) to be heard whilst significantly reducing other potentially harmful noise based. NPL's input to the project was based, in part, on NPL capability developed under this project.
- LNE has joined a French industry consortium composed of Thales Systems Avionic, Dassault Systems and four SMEs with the aim of developing vibration energy harvesters to supply autonomous sensors for aircraft monitoring. This three year industrial project (RECAP) started in 2013 and will focus on the commercialisation of vibration powered 3D integrated sensors.

Policy:

- This project has had input into UK funding policy through the Technology Strategy Board energy harvesting special interest group (SIG). The project worked with SIG on the writing of a number of industry reports covering standards, materials sustainability, new materials and rectification, as well as attending and presenting at SIG workshops. These reports and workshops will provide information to industry and help to inform the Technology Strategy Board on funding strategies.
- NPL are represented on the scientific board of the ZeroPower FP7 co-ordination activity whose mission is to develop a strategic research agenda for energy harvesting in low power, energy efficient ICT. This will help ensure an important role for metrology and the output of this project within this sector.
- This project has had two articles published by Pan European Networks "Science & Technology" publication which provides information to policy makers in the European Commission as well as government agencies and departments across the continent of Europe.

List of publications

1 Stewart, M.; Weaver, P. M. & Cain, M. “Charge redistribution in piezoelectric energy harvesters Applied Physics Letters” 2012, 100, 073901

2 J. de Boor, C. Stiewe, P. Ziolkowski, T. Dasgupta, G. Karpinski, E. Lenz, F.Edler, and E. Müller “High temperature measurement of the Seebeck coefficient and the electrical conductivity” Journal of Electronic Materials 2013, Vol. 42, doi:10.1007/s11664-012-2404-z, p. 1711

3 Mauro Zucca, Oriano Bottauscio “Hysteretic modeling of electrical micro-power generators based on Villari effect”, IEEE Transactions on Magnetics 2012, Vol. 48, no. 11, pp. 3092-3095

4 Briscoe, J.; Jalali, N.; Woolliams, P.; Stewart, M.; Weaver, P. M.; Cain, M. & Dunn, S. “Measurement techniques for piezoelectric nanogenerators” Energy Environ. Sci. doi:10.1039/C3EE41889H

5 M.Zucca, O. Bottauscio, C. Beatrice, F. Fiorillo Modeling Amorphous Ribbons in Energy

6 Harvesting Applications IEEE Transactions on Magnetics October 2011, n. 10, vol. 47, p. 4421-4424

7 Briscoe, J.; Stewart, M.; Vopson, M.; Cain, M.; Weaver, P. M. & Dunn, S. Nanostructured p-n Junctions for Kinetic-to-Electrical Energy Conversion Advanced Energy Materials 2012, 2, 1261-1268

8 Ernst Lenz, Frank Edler, Sebastian Haupt, Pawel Ziolkowski, and Hans-Fridtjof Pernau Traceable measurements of electrical conductivity and Seebeck coefficient of β-$Fe_{0.95}Co_{0.05}Si_2$ and Ge in the temperature range from 300 K to 850 K Phys. Stat. Sol (c) 2012, Vol. 9, Nr. 12, p. 2432-2435

9 E. Lenz, F. Edler, and P. Ziolkowski Traceable thermoelectric measurements of seebeck coefficients in the temperature range from 300 K to 900 K Int. Jour. of Thermophys. DOI 10.1007/s10765-013-1516-x

10 Rado Lapuh Ushering in new standards for energy harvesters The Engineer 12th November 2012

11 Briscoe, J.; Jalali, N.; Woolliams, P.; Stewart, M.; Weaver, P. M.; Cain, M. & Dunn, S. Measurement techniques for piezoelectric nanogenerators Energy Environ. Sci. doi:10.1039/C3EE41889H

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