

Metrology for Energy Harvesting

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Abstract – Energy harvesting is the use of e.g. thermocouples or piezoelectric generators for the conversion of ambient energy resulting from human activity and environmental energy flows in the form of waste heat, movement and vibration, into usable electrical energy. In the described project traceable methods for measuring energy, power and efficiency are being developed

Keywords (Energy harvesting, metrology, efficiency).

1. INTRODUCTION

If only a small percentage of the environmental energy could be used, it was possible to reduce the amount of batteries needed to power small electronic devices and sensors. This led to a massive reduction of maintenance effort and costs. In addition the substitution of batteries with energy harvesting devices reduces the amount of batteries which pollute the environment with their contained lead, mercury and cadmium at the end of their life-cycle. The manufacturers of energy harvesting devices need to compare the efficiency and the output power of the different possible set ups and any user of energy harvesters needs realistic and comparably performance data to decide which device suits his needs best. Depending on the source of energy in many cases the output signals of the harvesting devices may be quite small, non-sinusoidal, aperiodic and not stationary. This complicates reliable traceable measurements a lot.

In September 2010 an international project “Metrology for Energy Harvesting” on the basis of the EMRP (European Metrology Research Program) energy call started. Participants are the following national metrology institutes:

PTB	Physikalisch-Technische Bundesanstalt, Germany
CMI	Chesky Metrologický Institut, Czech Republic
INRIM	Instituto Nazionale di Ricerca Metrologica, Italy
LNE	Laboratoire nationale de métrologie et d'essais, France
MIKES	Mittatekniiikan Keskus, Finland
NPL	NPL Management Limited, United Kingdom
SIQ	Slovenski Institut za Kakovost in Meroslovje, Slovenia

The aim of the project is developing essential metrologies to support industrial exploitation of thermoelectric and vibrational energy harvesting technologies, with an emphasis on microscale energy

generation and an excitation input found in real-life scenarios.

2. STRUCTURE OF THE PROJECT

The work in the project is divided into seven workpackages, each having a workpackage leader and two or more further active participants:

TABLE I. List of workpackages

Number	Title	Participants, WP-leader in bold
WP1	Conversion efficiency of microgenerators	PTB , NPL, INRIM, LNE
WP2	Figure of merit of macroscopic thermoelectric reference materials	PTB , NPL, MIKES
WP3	Metrology for nanostructured thermoelectrics	PTB, NPL , MIKES, CM
WP4	Piezoelectric and magnetic materials for energy harvesting from macro to nano-scale devices	NPL , INRIM, LNE, CMI
WP5	Traceability for small non-sinusoidal signals	PTB , INRIM, SIQ
WP6	Creating Impact	PTB, NPL , INRIM, LNE, MIKES, CMI, SIQ
WP7	Management and Coordination	PTB , NPL, INRIM, LNE, MIKES, CMI, SIQ

The seven workpackages are defined as follows:

2.1. Conversion efficiency of microgenerators

The aim of this work package is to develop traceable metrology for the evaluation of conversion efficiency in micro-generators.

Microgenerators convert thermal or mechanical energy into electrical energy. The conversion process uses various types of materials, as there are thermoelectric, piezoelectric and magnetic materials. This requires a detailed understanding of the energy conversion processes. The work will develop techniques for simultaneous measurements of thermal, mechanical and electrical signals, the relationship of input power and energy to output, and impedance matching. In general, the measurement techniques developed here will assist in the fabrication of more efficient microgenerators. For the determination of the conversion efficiency, guidelines for best measurement practice will be prepared. International recognition of these methods will be achieved by a comparison.

2.2. Figure of merit of macroscopic thermoelectric reference material

The aims of this work package are the development of precise and traceable measurement methods and of a suitable measuring system for the determination of the Seebeck coefficient of macroscopic thermoelectric bulk materials as well as the certification of reference materials for Seebeck coefficients. For these reference materials the thermal and electrical conductivity will also be determined in a traceable way to allow a traceable calculation of the corresponding figures of merit.

Thermoelectric materials convert heat into electrical energy. Not all of the thermal energy can be transformed into electrical energy and the traceable determination of the efficiency of thermoelectric converters is crucial to enable a fair competition at the European and international level. The performance of this energy conversion scales with the thermoelectric figure of merit of the active material, which is defined as $ZT = S^2\sigma T/\kappa$, with S , σ , κ and T are the Seebeck coefficient, the electrical conductivity, the thermal conductivity and the absolute temperature, respectively. There is a fierce international competition for improving the figure of merit, but this competition may be distorted when there is no undisputed reference material with known thermoelectric properties, which can be used to validate testing methods and allow a reliable benchmarking of thermoelectric materials.

2.3. Metrology for nanostructured thermoelectrics

The aim of this work package is to develop reliable and accurate metrology of thermoelectric materials properties at a scale below 100 nm using a variety of devices such as thin-films and nanostructured bulk sample. The accuracy of these new methods will be assessed against the traceable measurement system developed in WP2. All the measurements of nanoscale dimension are calibrated using traceable artefacts that will be produced at NPL. This work package is separated into three tasks, each developing a new technique to measure and validate important materials parameters at the nanoscale. Specific materials to be studied include:

- Epitaxial layer of SiGe with thickness of about 100 nm and Ge content lower than 10 %
- PbTe/Te multilayers grown with molecular beam epitaxy
- Bi₂Te₃/Sb₂Te₃ multilayers grown with molecular beam epitaxy.

All the activities will examine these samples as a complete set of materials' properties is needed to compute their figures of merit ZT . The samples will be sourced in the form of 4" wafers. An optional Al₂O₃ layer of about 30 nm – 80 nm will be provided to facilitate measurement using the 3ω method. The wafers will be cut and post-process before measurement in NPL's clean room.

2.4. Piezoelectric and magnetic materials for energy harvesting from macro to nano-scale devices

The aim of this work package is to develop reliable and traceable metrology processes for the evaluation of the electro/magneto-mechanical coupling in piezo and magnetic materials and structures for energy harvesting applications.

A novel broadband energy harvesting facility will be designed and manufactured to measure energy coupling in devices subjected to non-sinusoidal broadband vibration.

- A novel piezoelectric active stage will be designed and manufactured to provide direct electronic control of the complex vibration profile.
- Traceable Laser Doppler Vibrometry (LDV) will be used to measure the vibrational characteristics of different structures for macroscale and MEMS scale energy harvesting
- Novel spectral analysis techniques will be developed at LNE to provide traceable measurement of the non-linear electrical response to the quantified non-linear mechanical excitation. Deep Level Transient Spectroscopy (DLTS) measurements will be used for the validation of the harmonics analysis technique.
- Finite element analysis modelling will be used at NPL to relate materials measurements to vibrational response and energy coupling at the device level. The model data will be validated by the experimental data provided in these latter work packages.
- Develop new tools to 'bridge the gap' between macroscale and the nanoscale for energy harvesting. A novel miniaturised "Berlincourt" test will be integrated with a Scanning Electron Microscope to provide scanning measurement.
- Develop FEA models relating microstructure (orientation, texture, domain structure etc) to materials' piezo response and energy coupling.
- PFM capability will be extended by adopting new and complementary techniques to measure direct piezoelectric and magnetoelectric properties using well defined local force generation.
- Nanostructured and transparent materials' magnetic properties will be studied using scanning near-field optical microscopy with a polarisation sensitive detector, and modelled using Time Domain Finite Difference methods

2.5. Traceability for small non-sinusoidal signals

The objective of the work package is to develop measurements of non-sinusoidal, aperiodic and non-stationary electrical energy output and develop the necessary traceability to SI.

The measurement of the efficiency of micro-harvesters will require the measurement of parameters of the input quantity, e.g. mechanical, and the corresponding output electrical quantities (voltage, current, power, energy) delivered to the load, which is typically the energy storage electronics. Because of the intrinsic nature of the input quantity, electrical output quantities will be non-sinusoidal, and often nonperiodical or even non-stationary. Commercial instrumentation aims on measurement of sinusoidal waveforms that may be slightly distorted, i.e. superposed by some harmonics. It does not achieve the specifications needed for quantities as described above, like frequency range, dynamic range, sensitivity and memory depth to precisely measure rare events. Existing devices for acquiring small irregular signals, e.g. for healthcare, lack precision or

traceable calibration. The general objective of the workpackage is to develop such devices and provide them with the necessary traceability to the SI.

The typical waveforms specific to different microharvesters will be investigated and characterised according their parameters, e.g. frequency, crest factor, dc content etc. These parameters are the basis for the development of measurement strategies, e.g. sample rate for digitizing or the appropriate type of analogue-to-digital (a/d) converter. Algorithms will be identified or developed to process the sampled data and obtain the required signal parameters, the most important of them being the effective amplitude and power. Finally an uncertainty analysis will be made.

A set of RC loads, having known impedance and mimicking the basic input properties of a dc-dc converter thereby taking into account the strong load dependency of the energy harvester together with a sampling system will be developed for the characterisation of the harvesters.

The traceability to SI electrical units will be obtained by calibrated voltage signals, either sinusoidal for point wise calibrations in the frequency spectrum or nonsinusoidal, for example, frequency combs covering the bandwidth or sub-bandwidths of the particular measurement being performed. These signals will be in turn traceable to dc measurements through ac-dc transfer with multijunction thermal converters. Current and phase quantities will be calibrated with standard ac loads as calibrated ac resistors and capacitors. The calibration will be performed periodically in an automated manner.

2.6. Creating Impact

Activities in this work package are:

- New metrology techniques and methods for the assessment and improvement of integrated micro-/nano-generator systems
- Publications of work at key conferences, key journals and appropriate trade press
- Training courses on how to use the techniques developed will be created and presented to our industrial collaborators and at appropriate conferences
- An Improved measurement infrastructure for energy harvesting devices. This will support the development of electrical generators exploiting all types of conversion of thermal and mechanical energy into electrical energy, with an emphasis on small-scale devices
- Advertisement of the infrastructure that will become available, e.g. articles in trade press, web pages, electronic (email) updates
- A set of industry measurement good practice guides for energy harvesting
- Inputs to standards relating to Energy Harvesting, leading to improved standards that can support faster product development
- Identify suitable standards bodies and JRP-Partners to link to these bodies
- Review the bodies' attended and likely uptake of JRP results

- Closer relations between industry and the European metrology and research community
- Knowledge transfer implies a one-way transfer of knowledge from researchers/scientists to industry. We prefer the term 'knowledge exchange' as it enables the two-way flow of knowledge and information between industry and the science base – to mutual and sustainable benefit. The following activities are proposed:
- Electronic newsletter for quarterly dissemination of news, events and findings
- Website – rather than invest time and resources in a new site, the consortium will integrate its activities into the several excellent websites, which already support the development of new energy harvesting technologies such as www.energyharvestingjournal.com and various regional networks such as the Smart Soldier and energy-harvesting EPSRC network in the UK.
- Media relations – feature articles in print, broadcast and online media (including participation/quotes from industry partners/beneficiaries)
- Annual survey and publication of industry needs (from top 100 companies): This data will be provided through our Industry User Group.

2.7. Management and Coordination

Besides the necessary reports this workpackage will deliver

- a document management system at the start of the project
- a kick-off meeting
- an agreed IP strategy
- a mid-term meeting
- a final video conference or meeting

To achieve these deliverables, an easy to use and therefore timesaving way of communication has to be setup. This comprises setting up a document management system (dms) by the coordinator and organising video conferences to enable the discussion of the reports and the further steps of the project including discussions of changes of the course of the project.

3. CONCLUSION

After the three years of project duration there will be the measurement infrastructure to characterize energy harvesters of various types as well as thermoelectric reference materials and to calibrate instrumentation equipment for these purposes at the national metrology institutes involved.

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