EnABLES: European Infrastructure Powering the Internet of Things

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1 Abstract

The mission of EnABLES is to open up key research infrastructure in the Internet of Things (IoT) to all European researchers, from both academia and industry. Six research Institutes together with 5 knowledge hubs are providing access to researchers to enable them to create 'self-sustaining' energy solutions to 'power the internet of things' based on energy harvesting, storage, micro-power management and system integration activities.
This paper provides an overview of the reasons why EnABLES is needed, particularly for enabling researchers address key challenges such as extending battery life of wireless IoT edge devices, and, where possible, eliminating the need for battery replacement. The ultimate goal of EnABLES is to create a 'starting community' to foster collaborations to address these challenges and opportunities & accelerate technology development.

The 2 primary approaches used in EnABLES are outlined:-
(i) A transnational access (TA) and virtual access (VA) program open to all external stakeholders to do free-of-charge feasibility studies leveraging from the facilities and expertise of EnABLES partners.
(ii) Joint Research Activities (JRAs) between partners. (Some examples of JRA activities are outlined at high level).

Simulations and data libraries are retained in an open access repository with an emphasis on creating standardized and interoperable parts and understanding their system level behaviour. EnABLES also fosters internal collaboration between partners (JRAs) guided by needs and opportunities. A key goal of the project is to create standardised and inter-operable libraries of parts & simulation tools for optimising system level performance

2 Introduction

EnABLES is a €5.2M EU research infrastructure project that started in Jan 2018 with the mission to create access to research infrastructure to allow 'self-sustaining' energy solutions to 'power the internet of things' based on energy harvesting, storage, micro-power management and system integration activities. Simulations, data libraries, equipment and expertise access, along with feasibility studies, can all be accessed in a fast-track manner via a Transnational Access (TA) and Virtual Access (VA) program. It also funds Joint

Research Activities (JRAs) between partners that are designed to improve the technology on offer through both TA and VA. www.enables-project.eu
The world will have 1 trillion IoT devices by 2025. Most of these will be wireless edge devices which means a portable power source (e.g. battery) is needed. For many applications it is critical to maximise battery life and eliminate the need for battery replacement where possible by developing energy harvesting solutions and/or finding ways to reduce the power consumption of devices.
To address this academic and industry developers need to work together to collaboratively develop application orientated solutions. EnABLES addresses this by building an ecosystem for collaboration initially creating a 'starting community'. It provides external fast track access to expertise and laboratories with over 130 researchers & €2Bn worth of infrastructure. The project funding means that that free-of-charge access is available to all to do feasibility studies (paper, simulation, characterisation, prototypes) that accelerate development and impact of 'self-sustaining' IoT devices.

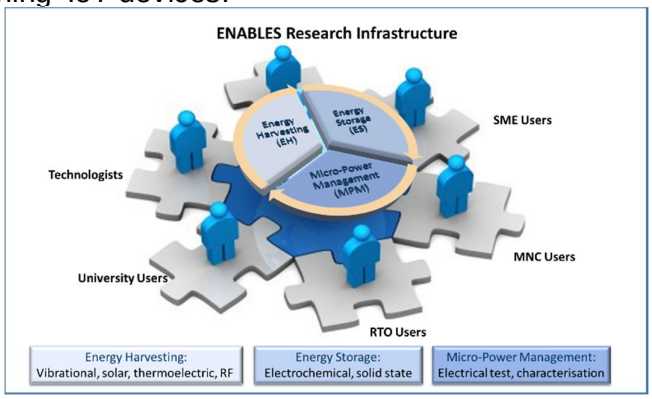

Fig. 1: Access offering and integration of the EnABLES Research Infrastructure network

3 EnABLES Rationale

IoT edge device sensors need to be 'invisible', unobtrusive and simple to integrate on, in and near people and the operating environment. Most applications require them to be miniaturised, energy-efficient and autonomous so that it is portable/wireless and self-sustaining. At present the 'power IoT user community' of academic researchers and technologists struggle to develop industry-relevant solutions to this challenge as they have no access to integrated state-of-the-art test structures, data and simulation tools that would allow them to assess and optimise their innovations. Similarly, SMEs have limited access to characterisation tools and prototype platforms. All these impede realistic implementation and deployment in real-life scenarios.

EnABLES address this challenge with a paradigm shift in providing a European-wide direct access route to relevant world-leading expertise, advanced equipment and state-of-the-art technologies linking new scientific knowledge with application-driven research. Avoiding fragmentation, this will lead to increased capacity and new capabilities in bespoke energy solutions and smart sensor system integration. It will enable the accelerated development of IoT innovation and capitalise on the global leadership of EnABLES.

EnABLES integrates key leading 'power IoT' related European research infrastructures (RIs) as one virtual combined entity of 6 access providers (research institutes) & 5 knowledge hubs of excellence comprising over 2Bn of capital investment and a critical mass of >130 researchers.

Fig. 2: Addressing the needs of the 'power IoT' user community

Free of charge access to unique infrastructure, world-leading expertise, advanced equipment and state-of-the-art technologies provides critical feasibility study 'seed funding' . It empowers academic researchers and technologists to advance energy harvesting, storage and micro-power management solutions for miniaturised autonomous sensors. Access ranges from materials & models to devices and systems and the access providers are working with the user community to accelerate adoption and innovation in real-life applications. This will deliver a mind-set change so that future energy management solutions are based on early concurrent and collaborative development of system-optimised IoT devices.

4 EnABLES Concept

EnABLES assembles a critical mass of people, knowledge, infrastructures and investment that covers the full innovation and value chains in energy management for autonomous miniaturised sensors. It combines resources covering the full innovation and value chain in the field – from fundamental studies to application-driven research and from materials & models to devices, circuits and systems. It brings together 6 research & technology centres (Tyndall, CEA-Leti, CEA-Liten, FhG-IIS, FhG-IMS and Imec-NL) to provide through a single-entry point, simplified access to world-leading expertise, advanced equipment and state-of-the-art 'power IoT' technologies. The consortium also performs complementary JRAs to improve its access offering. JRAs focus on developing the necessary tools, protocols, libraries and databases as well as advancing the state-of-the-art of prototype platforms, test structures, simulation models and tools. The consortium incorporates knowledge hubs of excellence (KIT/HIU, U-Southampton, U-Perugia, U-Bologna, POLITO) responsible for delivering frontier research across various disciplines including materials science, modelling & simulation, fabrication, device engineering, metrology, characterisation, circuit design and system integration. The EnABLES Virtual Access offering will leverage the Real Vibrations Database & Energy Harvesting Network Data Repository provided respectively by Knowledge Hubs U-Perugia and U-Southampton.

At the core of the consortium is a seamless infrastructure that accelerates the development of *application relevant* energy harvesting & storage modules (materials/devices/circuits). A unique ingredient of the project is the involvement of system integration expertise with the assessment of compatibility with potential applications. Modularity and interoperability are two enabling key features: modules can be easily added and combined from previous and present projects can be tested to allow assessment & benchmarking at material, device and system level.

Networking is an integral part of the EnABLES activities and a key factor for the success of the project in integrating and fostering the growth of 'power IoT' community fostering a culture of collaboration between the Access Providers, the Knowledge Hubs, and the user community. Networking activities provide feedback and exploitation pathways to the EnABLES consortium and user community through dissemination and communication.

For example access is provided to state-of-the-art energy harvesting, storage and micro-power management solutions as part of EU Programmes (H2020 & preceding programs), EUREKA programmes (MEDEA+, CATRENE frameworks, EURIPIDES, PENTA) and other Joint Programming Initiatives (ERA-NET, ECSEL). The consortium members are either actively participating or leading initiatives within industry-linked associations such as AENEAS, EPoSS, PSMA & ECPE.

5 Transnational Access (TA) Funding

TA funding comprises 40% of the EnABLES budget and is there to facilitate free of charge access by the user community to expertise and infrastructure of the EnABLES partners to do initial feasibility studies. It is complemented by JRAs to facilitate internal collaborations between partners and networking activities to accelerate collaboration between the stakeholders and accelerate the development of application orientated 'Power IoT' solution. A typical TA project is of the order of 10-20 days of work.

5.1 TA Process

A very simple process & support infrastructure is in place for academic and industry stakeholders to apply. Ease of access and inclusivity are key attributes, particularly those with little expertise in this area or in applying for funding to do early investigative work, with a drive to increase awareness of the potential of energy harvesting and related technologies to extend battery life & mobilise stakeholders to investigate and collaborate.

5.1.1 Sign Up and Enquire

There is a simple sign-up page that allows anyone become a member of the EnABLES network. Members will receive specific information on EnABLES technologies, details about upcoming events and news.

From the sign-up page a more detailed enquiry can be made. This important step will ensure that the specific technologies/facilities required are available and that the application is potentially eligible before going through the formal Access Application procedure. For example the application needs to have an international co-operation ('transnational') dimension and no more than 20% of the enquiries funded can be from outside the EU. A typical project is of the order of 10-20 days of work.

5.1.2 Apply

The EnABLES Access Application Form for transnational access is filled in. This will outline the type of access required and at which partner site. Application and selection is a rolling process. An Expert Committee will assess the technical feasibility of the proposal and make recommendations regarding the best suited EnABLES site/offering. An independent external Selection Panel reviews the Access Application Form and decides if transnational access will be granted. The primary criterion for selection are scientific merit and impact of the expected outcomes (e.g. possibility of a derivative project, creation of a strategic partnership between stakeholders, increased technology capability of applicant).

5.1.3 Access

Once Access is approved the applicant liaises directly with the Technical Point of Contact to organise access details such as schedule, visit(s) & required training and IP agreements.

At the end of the access period a User Report is completed outlining the project outputs and impacts. The data from TAs is made open source for the benefit of the entire 'power IoT' community with the notable exception of SMEs where the information may be sensitive and would impact their competitiveness.

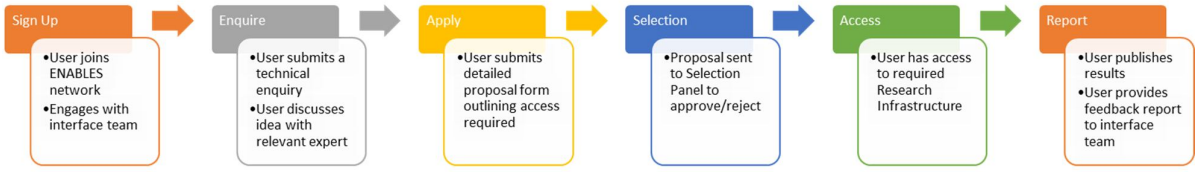

Fig. 3: EnABLES TA applications process

5.2 TA Offering

It is beyond the scope of this paper to describe the TA & JRA offerings in detail but reference to the website is recommended for an overview and ongoing developments. At a high level the Access offering is categorised as follows:-

(i) Advanced characterization & prototype assessment

Measurement techniques and tools are available to characterise the development of user prototypes in terms of their efficiency and/or reliability/lifetime. Assessment of innovative fabrication methods and implementation could be provided and feasibility studies undertaken to help users understand the scope for improvement and process compatibility with integration with other parts. For example assessing the integration of harvesting, storage and power management circuits into an integrated CMOS IC. Access could comprise using process equipment to do compatibility trials of their materials or devices or to leverage from expertise and virtual testing that guides considerations. This can be by way of a template or report. Similarly assessing potential integration of parts into a MCM (multi-chip module) or 3D packaging assembly.

(ii) Smart materials & test structures

Access to smart materials includes energy harvesting platforms (vibrational, solar, thermoelectric), micro-batteries and solid state supercapacitor systems. EnABLES will offer expertise, models and hardware to help test parts, evaluate prototypes and benchmark against known solutions. Examples include RF power transfer, AC-DC and DC-DC converters, sensor interfaces and power management chips.

(iii) Simulation tools & libraries

Modelling on materials, devices, circuits and systems is offered based on MEMS attributes such as physical, chemical, thermal, electrical, mechanical etc., to capture operational characteristics of parts and in combination with other elements. Models and libraries to assist with the successful deployment of self-powered IoT devices are also offered: for example (ii) ambient energy modelling – based on orientation, ageing, seasonality, frequency, amplitude, etc. over a given period, (iii) assessment of wake/sleep functionality required of IoT devices (& resultant energy and power needs), (iv) guidance on correct sizing of devices based on such operational and lifetime variabilities.

(iv) Testbeds & system optimisation tools

A service is provided to characterise IoT loads (e.g. WSN motes) and provide methodologies to optimise devices for energy harvesting compatibility. This should be of particular interest to industry partners who want to create a reference power/energy profile of their device. Users are encouraged to make parts available for characterization and then add to the access library. Assessment of ambient energies for a given application can be undertaken, taking variability into account e.g. frequency or amplitude of vibrations, irradiance levels depending on weather conditions (for PV).

6 Virtual Access

This leverages the *Real Vibrations Database & Energy Harvesting Network Data Repository* provided by the Knowledge Hubs of U-Perugia and U-Southampton.

Real Vibrations is the world's largest digital database of vibrations containing numerical time series and spectral representations of experimentally acquired signals from everyday life objects and people movements.

The Energy Harvesting Network comprises >175 people from wide range of companies and institutions. Its extensive data repository has been seamlessly linked to EnABLES.

Other partners also make their simulation software available through (L)GPL-type licences. Methodologies for the standardised creation and provision of VA library datasets is also being developed under EnABLES to ensure standardization, inter-operability and ease of comparison and integration of parts.

7 Joint Research Activities

JRA tasks aim at pushing the state-of-the-art as well as providing all the data and measurement methodologies necessary for benchmark specification and template standards. JRA activities are broadly defined under the following 3 categories.

JRA1: Libraries and metrology

JRA2: Component improvement

JRA3: Simulation Tool for power module sizing

These are underpinned by the 'technology pillars' of Energy Harvesting, Energy Storage, Power Management and System integration and are strongly interrelated. For example outputs from JRA3 can provide guidance to component developers in JRA2 on how to enhance system level performance of their parts. Similarly outputs from JRA2 provides valuable feedback to the library of parts available for improved accuracy and provides new parts to be added. Outputs from JRAs will be added to the TA offering and will take ongoing guidance from various EnABLES activities.

As EnABLES started a little over one year ago and JRAs started only in the past 6 months it is relatively early to report on progress, however a high level outline of intentions (with some useful references) is described below:-

Energy Harvesting – Wide-band non-linear harvesters appear promising as they are capable of exploiting common vibration sources across a reasonable frequency range. EnABLES is exploring novel bandwidth widening schemes to power IoT devices.

Novel high-performance thermoelectric materials are being explored with cutting-edge ab-initio simulations and innovative solutions for integration at the system level.[1]

[1] "Nanoparticle-in-Alloy" approach to efficient thermoelectrics: silicides in SiGe, N Mingo, D Hauser, NP Kobayashi, M Plissonnier, A Shakouri, Nano Lett. **9**, 711 (2009); Energy recovery system for an internal combustion engine arrangement, comprising thermoelectric devices, Luc Aixala, Patent US20120060775

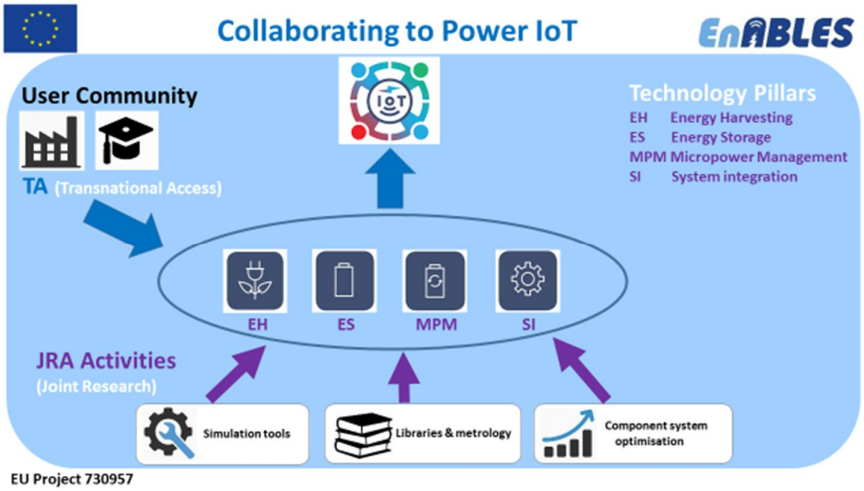

Fig. 3: EnABLES provides Ecosystem to Power the Internet of Things

Energy Storage – Nanoscale materials are explored that yield high-rate fast charging and discharge during (electrochemical) device interrogation.
Enhancing the cathode stability is needed to increase the energy density. In-situ TEM analysis of the materials and protective layers will assist with stability improvements.[2] Nanoscale protective films deposited by ALD/CVD can enable the use of higher energy density electrode materials and minimise contamination to improve device lifetime.
More energy dense sulphur-based cathodes can potentially provide ten times higher theoretical capacity. The substitution of liquid electrolyte with solid helps with safety, reliability & durability.[3] Room temperature ionic liquids are investigated, aiming to improve thermal properties, ion transport characteristics & safety features of polymer electrolytes.[4]
ALD/CVD deposition of protective materials at the active material (shell)/electrolyte interfaces will potentially enable significantly higher energy density, with lower cost, long life and high power capability.

Micro-Power Management – Efficient power conversion techniques particularly at low voltages & power levels are in development, coupled with accurate device & system level models. This incorporates understanding best trade-offs between intrinsic consumption of circuits & conversion efficiency.[5] CMOS enables advanced embedded micro-scale circuit optimizations with low intrinsic consumption.[6] Ambient energy sources can be very low & sporadic so provisioning for both homogeneous & heterogeneous sources must be made.[7]

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[2] Combination of in situ straining and ACOM TEM: A novel method for analysis of plastic deformation of nanocrystalline metals, A Kobler, A Kashiwar, H Hahn, C Kübel, Ultramicroscopy **128**, 68 (2013)
[3] High-rate V2O5-based Li-ion thin film polymer cell with outstanding long-term cyclability, C. Gerbaldi, M Destro, JR Nair, S Ferrari, I Quinzeni, E Quartarone. Nano Energy **2**, 1279 (2013); Nanocellulose-laden composite polymer electrolytes for high performing lithium-sulphur batteries, JR Nair, F Bella, N Angulakshmi, AM Stephan, C Gerbaldi, Energy Storage Materials **2016**, 3, 69.
[4] Newly Elaborated Multipurpose Polymer Electrolyte Encompassing RTILs for Smart Energy-Efficient Devices, JR Nair, L Porcarelli, F Bella, C Gerbaldi, ACS Appl. Mater. Interfaces **7**, 12961 (2015)
[5] Voltage transformer circuit and method for feeding power into an energy accumulator in a pulsed manner, L. Mateu, M. Pollak, P. Spies, Patent WO 2009/138180/PCT/EP/2009/003190; Voltage converter circuit and method for a clock supply of energy to an energy storage, M Pollak, L Mateu, P Spies, Patent US8498134; Rectifier circuit with ac short-circuit function and synchronized switch harvesting on inductor converter, L Mateu H Zessin, L Luehmann, P Spies, Patent WO 2013/050620 / PCT/EP2012/0699902
[6] A Nano-current Power Management IC for Multiple Heterogeneous Energy Harvesting Sources, M Dini, A Romani, M Filippi, V Bottarel, G Ricotti, M Tartagni, IEEE Trans. Power Electron. **30**, 5665 (2015)
[7] Micro-power Design of a Fully Autonomous Energy Harvesting Circuit for Arrays of Piezoelectric Transducers, A Romani, M Filippi, M Tartagni, IEEE Trans. Power Electron **29**, 729 (2014); Platform Architecture for Solar , Thermal , and Vibration Energy Combining With MPPT and Single Inductor, S Bandyopadhyay and AP Chandrakasan, , IEEE J. Solid-State Circ. **47**,2199 (2012)

Deep understanding of transducers (& collaboration with their developers) is necessary to design appropriate & effective power management circuits. Electronic interfaces based on recent commercial discrete components can provide a cost-effective solution with very low intrinsic consumptions (< 1 µA) but require simplified less efficient control schemes.

8 Networking Activities

Networking is an equally important EnABLES actvity particularly in addressing the high level vision of EnaBLES to 'form an ecosystem of experts' and 'starting community' to power the IoT. Networking activities are designed with the triple purpose of 'integrating, educating and growing' the community. This comprises several sub-task including

- Co-ordinating the internal and external network of stakeholders that manage the JRAs and TAs (e.g industry and academic advisors and reviewers of proposals) for scientific excellence, industry relevance, innovation and impact
- Organising summer schools & educational courses based on the technical expertise gathered within the consortium from both the TA projects and the JRAs. This provides a springboard to nurture a new generation of academic and industry users as well as access providers.
- Participating in/leading several workshops where researchers get the opportunity to learn about the state-of-the-art & discuss realisation towards specific applications.
- Development & maintenance of the website & various social media outlets (twitter, linked in, etc.) to disseminate project outputs, increase awareness & potential of 'power IoT' related technologies, share success stories, inform people of events, etc.

The success of the project will hinge on both the communication and advertising of the facilities and on the ability of the research community to gain simplified access to the technical platforms and thereby convert that access into useful research outputs.

9 Conclusions

EnABLES creates a research ecosystem and 'starting community' to create solutions to 'power IoT' particularly wireless edge devices based on energy harvesting, storage, micro-power management and their system integration. It provides free-of-charge access to external academia & industry as well as fostering collaborations between project partners to develop standardised and application optimised materials, devices and systems.

The Transnational and Networking activities supported and complemented by the innovation from JRAs provide a unique & disruptive infrastructure that maximises the learning and leverages from existing and emerging energy management technologies. EnABLES accelerates the development & validation of research solutions via

- Provision of common databases of materials, devices, circuits, models, ambient energy profiles, dissemination of information, cross-learning, etc.
- Collaboration between material, device and circuit developers to concurrently create parts that are pre-optimised for system integration, thereby, improving the suitability for commercialisation and accelerating their adoption
- Creation of a stable and on-going system-orientated infrastructure to attract commercial adopters who will assess, drive and 'pull' the technologies as components & combined entities to meet their application needs
- Bringing together upstream and downstream players in the value chain to develop, validate & optimise integrated systems compatible with real life applications.

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