EnABLES

European Infrastructure
Powering the Internet of Things

Research
Infrastructure
Position Paper

Research Infrastructure to Power the Internet of Things

Executive Summary

The Internet of Things (IoT) has the potential to address some of the world's most urgent challenges, from tackling the climate emergency to caring for the health of our population. IoT sensory devices can be placed on, in or near people, things or the environment to gather information from billions, even trillions, of sensors. This information is then analysed locally or over the internet to create an automated action.

However, to really benefit society, scientific and technological innovations are needed in the medium and long term to address the gap in powering these trillions of devices. Our aim is to make batteries outlive the IoT devices they power. At present, a typical battery life for a wireless edge device sensor is around two years or less. With most devices having an operational life of more than ten years, this leads to multiple battery replacements. This results in device downtime and maintenance trade-offs as well as major economic and environmental issues related to the manufacture and disposal of hundreds of millions of batteries every single day. In addition, it has meant that there are many untapped IoT applications in areas such as medical technologies, implantables and installations in harsh environments due to the criticality of having a reliable power source throughout the device lifetime.

To deliver the required battery life extension, we are working with our partners across the EU to foster and guide key 'power IoT' advances to harvest tiny ambient energies such as light, heat and vibration and converting them to electricity whilst being more efficient and clever in minimising the energy consumption of the sensors.

Thanks to the EnABLES European Research Infrastructure[1], the European Union (EU) already has a well-established scientific and technological leadership position in this area. Given the societal pay-off, including the opportunity to meet the EU Green Deal[2] objectives and to contribute to the UN Sustainable Development Goals[3], as well as the economic opportunities available, we have outlined additional actions to facilitate further advancement. These include easy and efficient access to the scientific expertise, state-of-the-art facilities and the technology platforms that are already available.

Overall, there is a real danger that the EU's strategic advantage and the momentum already created by EnABLES in alignment with these key recommended actions will be lost if a longer term sustainable power IoT infrastructure is not put in to place.

In summary, the actions are to:

1. Foster and grow the power IoT community by promoting and leveraging the platforms already created with specific measures to target the broader stakeholders (suppliers, integrators and end-users);
2. Strengthen support mechanisms for cross-border collaboration and secure availability of experts and state-of-the-art research infrastructure through transnational access;
3. Convert outputs of projects and feasibility studies into modular, standardised and inter-operable platforms and solutions enabling de-risked customisation and faster time to market;
4. Identify and execute appropriate supporting capital investments for equipment and infrastructure upgrades;
5. Create new synergies with scientific disciplines and technology domains across the extended ecosystem, particularly targeting the next generation of researchers and talent upskilling.

---

1 http://www.enables-project.eu/
2 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
3 https://sdgs.un.org/goals

The 'Power the IoT' challenge

Our 21st century world faces many challenges, from tackling the climate emergency, creating a pollution-free environment and the restoration of biodiversity, to ensuring clean energy, safe food and foremost caring for the health and well-being of an increasing and ageing population. Whilst the IoT is at its infancy compared to other engineering disciplines, it has already been recognised as a powerful enabling force to address the UN Sustainable Development Goals. The IoT is also a key enabler to 'transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use' as set out by the European Union (EU) in the European Green Deal.
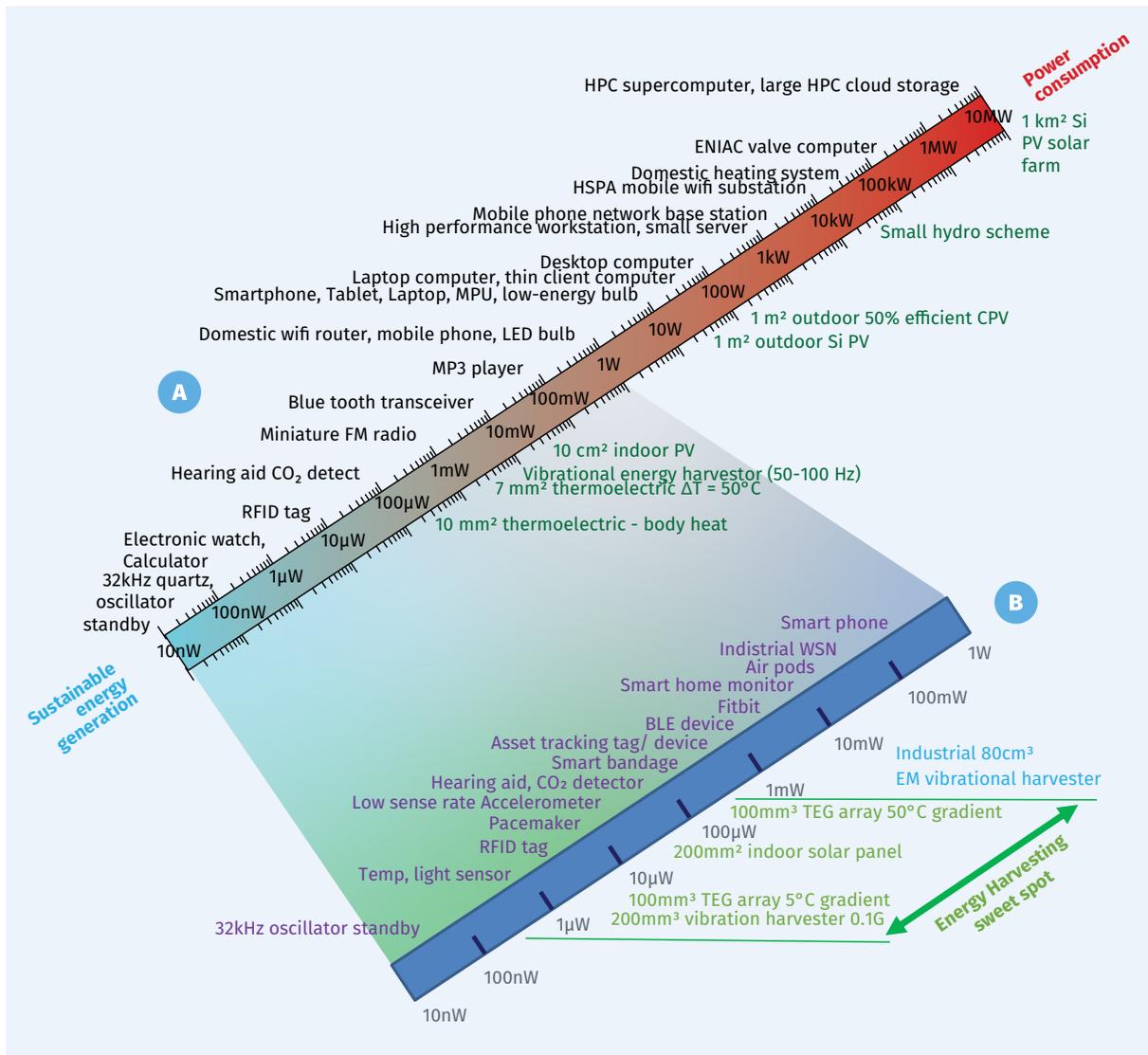

Fig 1. *Typical power consumption of (A) different ICT devices and systems[4] (B) IoT edge devices versus the power that can be generated from sustainable/renewable energy generation devices and systems.*

However, widespread adoption of IoT solutions hinges on overcoming a formidable 'power the IoT' gap (Fig. 1). IoT systems include:

- Sensors to measure physical properties such as temperature, light, humidity, occupancy, pressure and air quality;
- Aggregators and processors to transform and manage sensory data;
- A communication channel for wired or wireless data transmission.

The decision/alarm/action trigger can be made at the edge, gateway, database or cloud but for many applications there is a push towards edge processing making the energy gap even larger.[5] Each of the sensing 'things' at their heart, has to be able to store enough energy to sense, process and transmit relevant data. Common batteries are not sufficient to power the nodes throughout their lifetime, in particular when there is a heavy load in terms of sampling data size and frequency, local processing and transmission frequency, data and distance. In addition, the need to miniaturise IoT devices so that they can be retrofitted 'invisibly' on, in and near people, equipment, infrastructure and our environment further extends the gap.

Whilst higher energy density storage solutions offer a route to the 'power the IoT' challenge, the solution requires a more holistic approach because for most applications the difference between required and available energy is simply too large (typically of the order of 500%+, often much higher). An integration of multiple technologies is necessary; taking into account not only where energy is stored but also whether there is available energy to harvest from the environment as well as how to minimise energy consumption and optimise power overall.

However, there is, in the opinion of the authors, a sweet spot from around 1 nanoWatt to a few hundred microWatts, where real-life ambient energies from reasonably sized harvesters can have a significant impact on the battery life (Fig. 2).

---

5   https://efecs.eu/publication/download/ecs-sria-2021.pdf
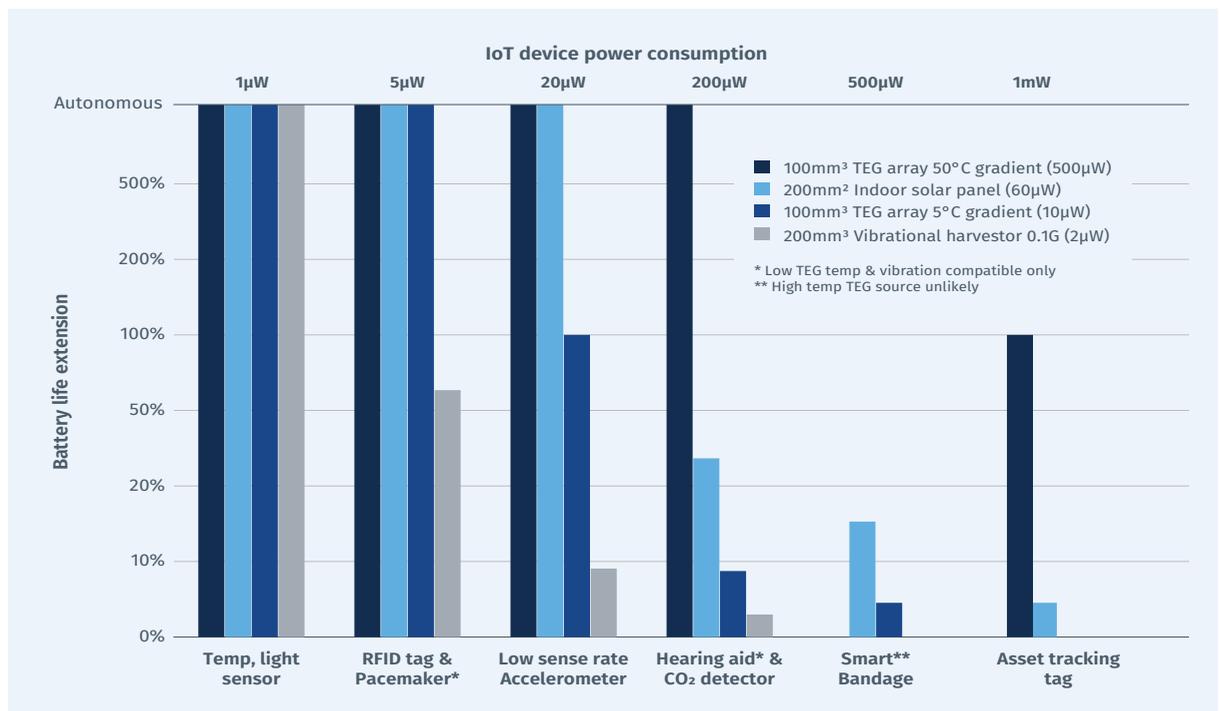
Fig 2. *Energy harvesting sweet spot for IoT edge devices / battery life extension impact.*

Autonomous powering is possible for many sub 100µW (microWatt) devices and the potential for using various types of ambient energy sources increases as the power footprint lowers. Similarly, if the power consumption of IoT devices is reduced to sweet spot (sub milliWatt) levels, there is the double impact of less drain on the existing power source and increased viability of adding relatively small energy harvesting devices to significantly increase battery life.

If stakeholders think about power at the early conceptual stages of IoT solutions in co-designing and selecting components, data gathering and processing architectures, significant battery life extension is possible. This is not just about minimising power consumption, it extends to understanding the operating environment and what types of energies could be harvested and stored to extend battery life. This concept and the relevance of scientific disciplines of energy harvesting, storage and power management (and their system integration) as enabling technologies is further elaborated in Fig. 3 and accompanying text.

Fig 3. *Scientific disciplines enabling the technologies to 'power the Internet of Things' for multiple applications*

Energy Harvesting

Better efficiencies are needed in converting the low level ambient energies (e.g. small temperature gradients for thermoelectrics, low level indoor lighting for solar cells, vibrations from body motion) that are available, typically in the µW range. A major challenge is to allow for their variability and intermittency. Key technologies include:

- Wideband vibrational harvesters;
- High-performance thermoelectric materials;
- New antenna designs for RF power transfer;
- MEMS & NEMS (Micro/Nano-Electro-Mechanical Systems) integration devices;
- Additive manufacturing.

Energy Storage

Primary storage devices need higher power and energy density with ultra-low leakage current. Rechargeable devices, in addition, must deliver hundreds of thousands/millions of cycles without significant degradation and be able to sink and source tiny (nanoWatts) amounts of energy. Storage solutions to manage load transients from µA (microAmps) to mA (milliAmps)

is critical. An increasing number of applications require operation in extreme environments. Key emerging technologies include:

- Flexible and printable battery form factors;
- Nanoscale materials with high-rate charging;
- Atomic Layer Deposition/Chemical Vapour Deposition of protective materials for enhanced energy density, with reduced cost, long life and high power capability;
- More energy dense sulphur-based cathodes to provide up to ten times higher theoretical capacity;
- Substitution of the liquid electrolyte with a solid one polymeric, ceramic or hybrid one for safety, reliability & durability.

Micro-power Management

The transfer of ambient energies to storage devices and its subsequent conversion to usable levels for the IoT load brings many challenges for PMICs (Power Management Integrated Circuits).

- Impedance matching techniques to maximise energy transfer;
- Novel power architectures to efficiently convert ambient energies (often at very low voltages and power levels) to usable levels;
- Self-start circuits to ensure device autonomy;
- Ultra–low (nW) quiescent current consumption;

- Digital mode control in order to be able to dynamically configure the operation mode of sensors, MCUs (microcontrollers) and transceivers to minimise their power consumption and only activate as needed;
- 'Multi-source', capability, managing a broad variety of ambient energy types;
- Condition monitoring of components to optimise charge management and detect anomalies;
- Integration/embedding of magnetics and MCUs offering exciting performance, cost reduction and size enhancements.

All of this needs to be underpinned by multi-modal *simulation models*. This area offers much scope from predicting device and system level energy generation, storage and usage based on ambient energies and IoT device configuration to offering significant assistance to potential adopters in predicting battery life and optimising component selection, particularly in *system integration*.

The following are real life examples of IoT applications and the related 'power IoT' opportunities/challenges. All of these were undertaken as feasibility studies under the EnABLES 'power IoT' research infrastructure transnational access programme.

Table 1. *Real life examples of IoT applications and the related 'power IoT' opportunities/challenges.*

Application sector	Health	Food	Smart buildings	Industry	Mobility
Client	EU SME	EU Research	US SME	European Start-up	EU Company
Challenge/ opportunity	Power source solution for smart wound-dressing	Low-power solutions for Fishbit devices	Self-power window sensor for room comfort	Synthesis & process investigation of energy storage device	Self-powered GPS tracking system
EnABLES support	Energy Harvesting /µPower Management	µPower Management/ System Integration	µPower Management/ System Integration	Energy Storage (materials and processes)	Energy Harvesting (Vibration+Solar)
Potential impact	Battery life extension from 1 week to >1 month	Extend battery life of monitor from hours to days	Lower power consumption + use PV to extend battery life	High-capacity, high temperature resistant thin film batteries	Indefinite battery life

Critical role of a European Research Infrastructure 'Powering the IoT'

Deep Expertise, Advanced Equipment and State-of-the-Art Platform Technologies

At present the 'power IoT user community' of academic researchers and technologists struggle to develop industry-relevant solutions to this trillion sensor 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.

Cost hampers the adoption of any new technology, thus funding from government agencies and venture capitalists is needed to accelerate development. We lack an established technology ecosystem with tight collaboration between material innovators, start-ups and device developers and material suppliers to develop specific solutions and establish common standards to facilitate reliable production processes. For example many efforts are being undertaken to develop flexible secondary batteries for shapeable, wearable applications. These devices suffer from severely limited capacities compared to commercially available parts before even considering packaging and long term stability issues. Innovative materials are needed to enhance energy density, safety and smart packaging features. In addition, specific fabrication technologies (e.g. 3D, laser or inkjet printing) may enable large-scale production at reduced cost.

The existing European Research Infrastructure for Powering the IoT, EnABLES, has brought a community together to address these challenges through providing a European-wide direct access route to world-leading expertise, advanced equipment and state-of-the-art technologies, linking new scientific knowledge with application-driven research. EnABLES integrates key European research infrastructure shared among six institutes. Together with five knowledge hubs of excellence from academia, EnABLES nurtures a 'powering the IoT' community with a mind-set change in how parts and systems are developed based on rapid access to advanced research infrastructure. EnABLES promotes the progress of wireless IoT devices and miniaturized, autonomous sensors, the development and integration of energy harvesting and energy storage solutions, and the advancement of energy management solutions within self-powered smart sensor systems. Avoiding fragmentation, this leads to increased capacity and new capabilities in bespoke energy solutions and smart sensor system integration.

The current paradigm must be exploited and leveraged to maximum effect to seed future high impact outputs and create ready-made future 'power IoT' platforms that are inter-operable and standardised for deployment. Engraining the mind set of 'thinking about power' at the very early conceptual stages in designing IoT systems will yield many new synergies, extending beyond electronics to ICT and MEMS, software, industrial design and data analytics spanning a broad variety of end applications such as medtech, smart cities, agri-tech, environmental monitoring and industry 4.0. This will allow for the full potential of IoT innovation to be exploited in addressing our societal challenges. A European Research Infrastructure for Powering the IoT fosters the community with brand new ideas and engineering solutions and a next-generation of people, thereby enabling the accelerated development of innovation in the nascent IoT field and putting the EU in a global leadership position both in academia and industry.

Creating an International Ecosystem

As outlined previously we need to think beyond the 'traditional' ecosystem of power IoT related scientific disciplines (energy harvesting, storage, power management and their system integration). This new paradigm needs to be extended to include other related enabling technologies for a system level approach that focuses on the intended real life use case applications. For example, MEMS/NEMS covers a broad range of related technologies that includes PSiP (Power Supply in Package), PwrSoC (Power Supply on Chip) and the industrial design of IoT devices.

This provisions for the sensors and ambient energy transducers to be 'exposed' to the operating environment whilst making them sufficiently ruggedised to operate reliably over time. *Low Power Electronics* technology platforms will provide many of the required generation, conversion and storage materials, components and circuits needed, scaling down from

W to μW. **ICT** technology platforms provide the key connectivity that is needed for Wireless Sensors to reliably process, send and receive data using **Wireless Communications** and Low Power **MCUs** (micro-controller units) whilst minimising power consumption. This is all driven by the IoT Applications envisaged e.g. industry 4.0, wearables, micro-grid energy management, connected & autonomous vehicles. Requirements engineering for the given use-cases is also a key topic where power optimization has to be considered at all levels. The entire ecosystem of stakeholders needs to be captured from **Developers** & **Suppliers** to **Integrators** and **End Users**.

To realise this vision, all stakeholders need to be involved at the early development stage to ensure parts are standardised, inter-operable and system optimised. Each segment shown in fig. 4 can be sub-classified into technology elements such as software design, RF communications, data analytics and mechatronics.

Fig. 4: *'Power IoT' Ecosystem of Scientific Disciplines, Related Enabling Technologies, Stakeholders & Applications*

This is quite a complex ecosystem that is taking considerable time and effort to build but it is a critical step if we are to be successful in providing long battery life for IoT edge devices, enabling autonomous and reliable operation. EnABLES has already made significant progress in building such an ecosystem along with other initiatives. However, this needs to be supported by a long term, sustainable research infrastructure to foster collaborations, provide easy access to expertise and equipment and seed initial feasibility studies.

This helps to create standardised and inter-operable platforms, establishing shared repositories from such studies guiding and de-risking future 'power the IoT' technology developments for real life applications. It also guides future capital investements in research centres in alignment with stakeholder needs creating new synergies with scientific disciplines and technology domains across the extended ecosystem, particularly targeting the next generation of researchers and talent upskilling.

EnABLES Outputs and Impact

EnABLES has already accumulated significant evidence of the impact of a 'power the IoT' Research Infrastructure. Table 2 presents some examples of outputs already achieved/underway via Joint Research Activities (JRAs) as well as Transnational Access (TA) offerings. Further examples can be found later in table 3 (TA testimonials).

Table 2 – *EnABLES Impactful Innovation Examples*   *Joint Research Activity*   ** Transnational Access Activity*

Innovation		Impact/Advance beyond SoTA
	Micropower discrete & PMIC circuits	Capable of managing micropower conversion and extending battery life. Many ambient energies are at this level and cannot currently be used and intermittent IoT current peaks may affect battery life.
	Digitally controlled PMIC with ultra wide I/P, O/P voltage power range*	Harvest an unprecedented broad range of ambient energies. High conversion efficiency even at the sub 10µW level. Input voltage 0.1-4.5V, output 1-4.5V. Typically will deliver a x2 to x7 battery life extension, with autonomous operation possible for some applications.
	TF inductor compatible with Si fabrication*	Ability to embed inductors onto silicon. This will give us miniaturised high frequency, higher density, lower cost power sources.
	Solid-state Li-based batteries *	Rechargeable batteries with high energy density, stable cycling at ambient temperature and safety features due to novel electrodes & highly conducting solid-state crosslinked polymer-based electrolytes. Usable over a much broader range of real life applications.
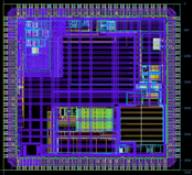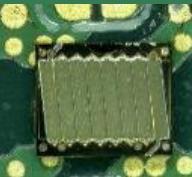
	Nano materials for storage –cathodes, electrolytes*	At least X10 times higher energy density, longer life, wider temp range. Disruptive impact on size and battery life and the number of feasible IoT applications.
	Printed electronics *e.g. 3D printed Electrolyte gate transistor	Use of 3D printing of passives and transistors with non-toxic materials. More environmentally friendly. Solid printed re-chargeable batteries. Effective for wearables and non-uniform surfaces.
	Flexible antennae for wearables *	Seamless embedding of long range antenna into clothing, bandages, straps, etc. Becomes possible to send sensor data for assisted living, sports, patient monitoring, human centric internet applications.
	Non-linear vibrational harvester *	Harvest sustained energy over a broad band of vibration frequencies and amplitudes (as is found in most applications). Conventional solutions work effectively over a very narrow band.
	Self-tuning vibrational energy harvester **	Working with an SME to develop a unique ASIC which samples vibrational harvester properties and tunes to maximise energy extracted.
	Self-powered wireless sensor platform BlueTEG **	Hardware consisting of commercial thermoelectric generator, micro power management, Bluetooth Low Energy wireless module. Fully powered by at least + or -4K thermal gradient on any kind of pipe, duct or housing which gets hot or cold during operation.
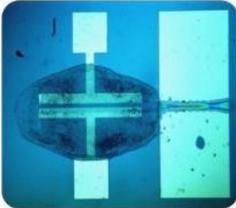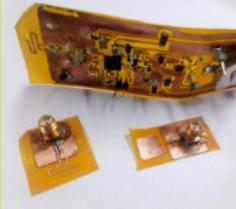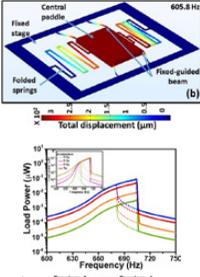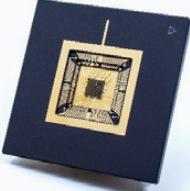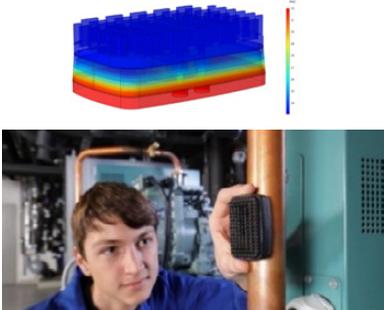
The JRAs are already creating disruptive synergies between the partners, combining their expertise and technologies to create the technology platforms of the future, guided by the needs and applications of the power the IoT ecosystem. In some cases, an EnABLES partner is developing a technology platform taking into account (and inter-operable with) the future needs of other partners. In others, partners' technologies are combined into high impact innovations. The results allow for improved offers, for example with respect to miniaturisation or enhanced integration:

Impact on miniaturisation – Tyndall is developing thin film CMOS compatible planar inductors for lower (cold-start) voltage operation in PMICs and ancillary circuits are being developed by Fraunhofer and UNIBO. They would eliminate bulky transformers and significantly reduce parts size as well as increasing extraction levels from ambient energy sources.

Impact on integration – In energy storage nanomaterials innovative high density storage solutions by new nanomaterial and polymers were created for flexible/wearable applications through integration into clothes, uneven surfaces, bandages, enclosures, etc.
- Innovative high entropy oxides and printable safe, solid-state polymer-based electrolytes (KIT & POLITO)
- Laser induced graphene for high surface area negative electrodes (Tyndall)
- High entropy oxides for battery electrodes (KIT & Tyndall)
- New Raman characterisation methodology for battery electrodes within stack assemblies (CEA)

The TAs give examples of how access subscribers are already deriving benefits and understanding how existing technologies can enhance their own platforms or resolve application issues.

The testimonials in table 3 provide further examples of the impact of undertaking EnABLES feasibility studies.

Table 3 – *EnABLES Transnational Access Testimonials*

🇮🇪 **Irish SME:** Service provider for remote autonomous level monitoring in silos (FhG-IMS).		
	Dust formation during filling of silos causes a dust deposit on the optics of the sensor creating problems with level detection. The study assesses photovoltaic energy harvesting for the supply of the IoT sensor and lens cleaning and builds an initial demonstrator.	*"Our sensors sit in silos typically containing powder that get congested. The feasibility study showed us that careful power management at controlled intervals would enable us to activate self-cleaning sensors. Expertise from EnABLES in future could help us select the optimal sizing & intervals of the sensor cleaning system that would last >10 years. This dramatically reduces the maintenance needed on silos & related costs."*

🇦🇹 **Austrian SME:** Energy harvesting power supplies for GPS trackers on railway trains (FhG-IIS).		
	Completely self-powered autonomous operation was found to be realistic for the specified use-cases. The technology is planned for adoption in a German public funded project which will lead to a commercialised product that increases the safety of assets and goods and ensures an on-time delivery.	*"Very smooth process from first contact. Availability of Fraunhofer IIS was really good. Answers and technical input were punctual and very accurate. Very direct collaboration, the agenda of the project and the setup was clear to everyone. In addition, two-weekly conference calls helped to fulfil the aim of the project."*

🇨🇭 Swiss-based multinational: Determine whether RFID technology can be used to wirelessly monitor the temperature of heated food in a combined device consisting of an oven & microwave (FhG-IMS).
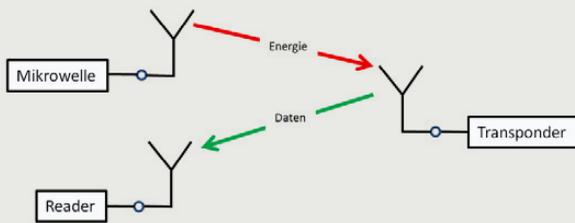
The wireless sensor transponder is supplied with energy via an independently transmitted electromagnetic field (microwave signal) and the sensor transmits data to a separate receiver station, called a reader.

"Fraunhofer IMS provided excellent knowledge on RF energy harvesting and wireless data communication. We are specialised in supplying sensors e.g. temperature sensors and sensor systems for many applications. The sponsorship by EnABLES allowed us to push into a new technical field of energy harvesting and wireless communication. To open up new applications, energy-autonomous sensors are an important factor in the future. We gained internal knowledge and were enabled to estimate necessary modifications on our products to allow an implementation of the studied technology. With the RF-harvesting technology we plan to expand our portfolio and serve a much bigger market in the future."

🇮🇹 Italian University: Integrated software/hardware design approach to fabricate power-efficient multi-insulator tunnelling diodes for future 5G/IoT RF energy harvesting applications (Tyndall).

This was a study combining simulation models and hardware design methodologies to enable optimised tunnelling diode development and fabrication for real life applications of RF energy harvesting.

"The EnABLES contribution to our project is fundamental as it consummates the theoretical study with a real-world implementation of the suggested model. All the project members are just experts and liaise very well throughout the different project phases. The EnABLES application process was very simple and the outputs will guide and accelerate our development of tunnelling diodes from the fundamental concept phase. With the realized prototype, we aim to optimise power harvesting for millimetric frequency range IoT devices, where there is a surge of interest from commercial partners and make them ready for future commercial applications."

🇳🇱 Dutch SME: Characterise improved (as cast & annealed) TE materials for industrial applications (CEA-Liten).

Heat capacity properties were successfully measured up to 300°C confirming that the thermal conductivity reduction by doping precipitation is a viable route to reduce the thermal conductivity of thermoelectric materials. This will lead to higher power output TEG materials in the market.

"The dedication of the CEA team in providing the best measurement to support our development was an accelerator to give us valuable insight in the understanding of thermal conductivity reduction strategy for our doped material. This will result in materials that can deliver more energy in real-life applications. They provided all the required equipment and expertise to fulfill our need for this project and simplified the communication and the logistics. We highly recommend this free of charge and easy access to equipment and expertise to others."

Table 3 – *Continued*

🇺🇸 **US Engineering consultancy:** Characterize wireless sensor network system being developed to support a family of smart patch devices (Tyndall).

The feasibility study devised a methodology for characterising power consumption showing sensitivity to component selection and setting. It also created circuit and PCB layout recommendations so that in future designs it will be easier to decouple power consumption of individual components and circuits. This also makes it easier to simulate potential impact of using energy harvesting.

"Thanks to the EnABLES team and the EU for supporting my project. This gives us a solid basis for characterising and optimising power consumption of our next generation of devices as well as understanding the potential battery life extension if we use energy harvesting. This is an amazing transnational access program that provides little companies like mine to access billions of dollars in assets that never would have been available/affordable for us. Hope it continues and grows for others as well as our desire to utilise in the future. Thanks again for putting your resources to great use!"

Recommended Actions

It is critical to build an EU based sustainable 'power IoT' research infrastructure to an appropriate scale to create a sustainable green future, connecting people 'in the right place at the right time', fostering collaboration and accelerating the adoption of emerging technologies. This can be achieved by leveraging and sustaining the EnABLES international community already created and extending the stakeholder ecosystem.

Key actions identified to date are to:

1. **Foster and grow the power IoT community by promoting and leveraging the platforms already created with specific measures to target the broader stakeholders (suppliers, integrators and end-users).**
   _ This can be achieved by extending and expanding the research infrastructure, methodologies, data repository (technology platforms, simulation models, webinars, standardised outputs, use cases, etc.) and network/ecosystem created by EnABLES beyond its project life (mid 2022).

2. **Strengthen support mechanisms for cross-border collaboration and secure availability of experts and state-of-the-art research infrastructure through transnational access.**
   _ The TAs and VAs (Virtual Access offering to ambient energy data repositories) from EnABLES have clearly demonstrated high impact scientific excellence that is driven by real life application needs (ref. table 2) and such offerings should be continued. They have also already seed-funded several follow-on activities. The JRAs are already creating the TA platforms of the future (ref. table 2). These successes call for a continuation of the TA programme to sustain the 'power IoT' pool of expertise and research infrastructure.

3. **Convert outputs of projects and feasibility studies into modular, standardised and inter-operable platforms and solutions enabling de-risked customisation and faster time to market.**
_ *This needs a 'champion' to demonstrate by leading. EnABLES is already doing this (e.g. creating a standardised template for characterising energy harvesting, storage and micro-power management components that has been already adopted on other projects.) Several JRAs show examples of co-development amongst partners creating standardised and interoperable technology blocks. Intensive and ongoing interactions with industry associations, standardisation bodies, research clusters, etc. is critical for standardisation and inter-operability. Many such entities have already subscribed to EnABLES and there is a timely opportunity to further mobilise these stakeholders to work together more coherently to achieve this goal.*

4. **Identify and execute appropriate supporting capital investments for equipment and infrastructure upgrades.**
_ *Strategically this needs to be done holistically examining the collective of research infrastructure equipment that is already in place throughout the EU rather than the silos of individual research institutes. A long term sustainable research infrastructure can provide the guidance and oversight for prudent and complementary capital investments throughout Europe. In turn mechanisms are then needed for such capital equipment and infrastructure to be made easily available transnationally.*

5. **Create new synergies with scientific disciplines and technology domains across the extended ecosystem, particularly targeting the next generation of researchers and talent upskilling.**
_ *An impressive set of synergies and an ecosystem of almost 500 stakeholders from 38 countries has already been created by EnABLES which in itself has > 130 'power IoT' experts within the 11 partners and generated over 100 enquiries. A key message is that it is not just about the current and next-generation of experts in energy harvesting, storage and micro-power management - it needs to include the related enabling technologies (e.g. MEMS,*

ICT, Sensors) as well as the end users and integrators (ref. fig. 4). In particular, the next generation of researchers needs to be educated and trained in both hard and soft skills and connected at an early stage to the entire 'power IoT' ecosystem. The webinars, summer schools, workshops and technical seminars such as those already underway by EnABLES serve this purpose and need to continue to reach out to all of these stakeholders and this initiative needs to continue beyond its project life.

The recommended actions will ensure the EU's strategic leadership position. Overall, there is a real danger that the EU's strategic advantage and the momentum already created by EnABLES in alignment with these key recommended actions will be lost if a longer term sustainable power IoT infrastructure is not put in to place. Reliably gathering critical data using retrofitted autonomous wireless sensors is perhaps the biggest opportunity for the EU to meet its Green Deal objectives for 2030 and make our world a greener, more efficient, connected and safe place and the proposed sustainable 'Power IoT' infrastructure is a critical step towards achieving this.

About EnABLES

EnABLES is a €5M EU funded research infrastructure project, co-ordinated by Tyndall National Institute, and comprising 11 leading research institutes in Europe. It provides free transnational access (TA) to key European research infrastructures in powering the Internet of Things (IoT).

The mission of EnABLES is help users understand how 'battery life' can be extended to minimise and in some cases eliminate the need for battery replacement by using energy harvesting and related technologies (energy storage, micro-power management and their system integration).

This is done via a transnational access program opening up key research infrastructure to researchers from both academia and industry to undertake 'Power IoT' feasibility studies coupled with a joint research activity (JRA) portfolio demonstrating the impact of collaboration and developing application driven 'Power IoT' solutions for the future.

A key vision for EnABLES is to build a sustainable 'Power IoT' ecosystem with supporting technologies, standardised methodologies, databases, tools and infrastructure enabling stakeholders to come together and collaboratively develop system optimised long battery life power solutions for IoT devices.

Cleanroom facility at
Tyndall National Institute.
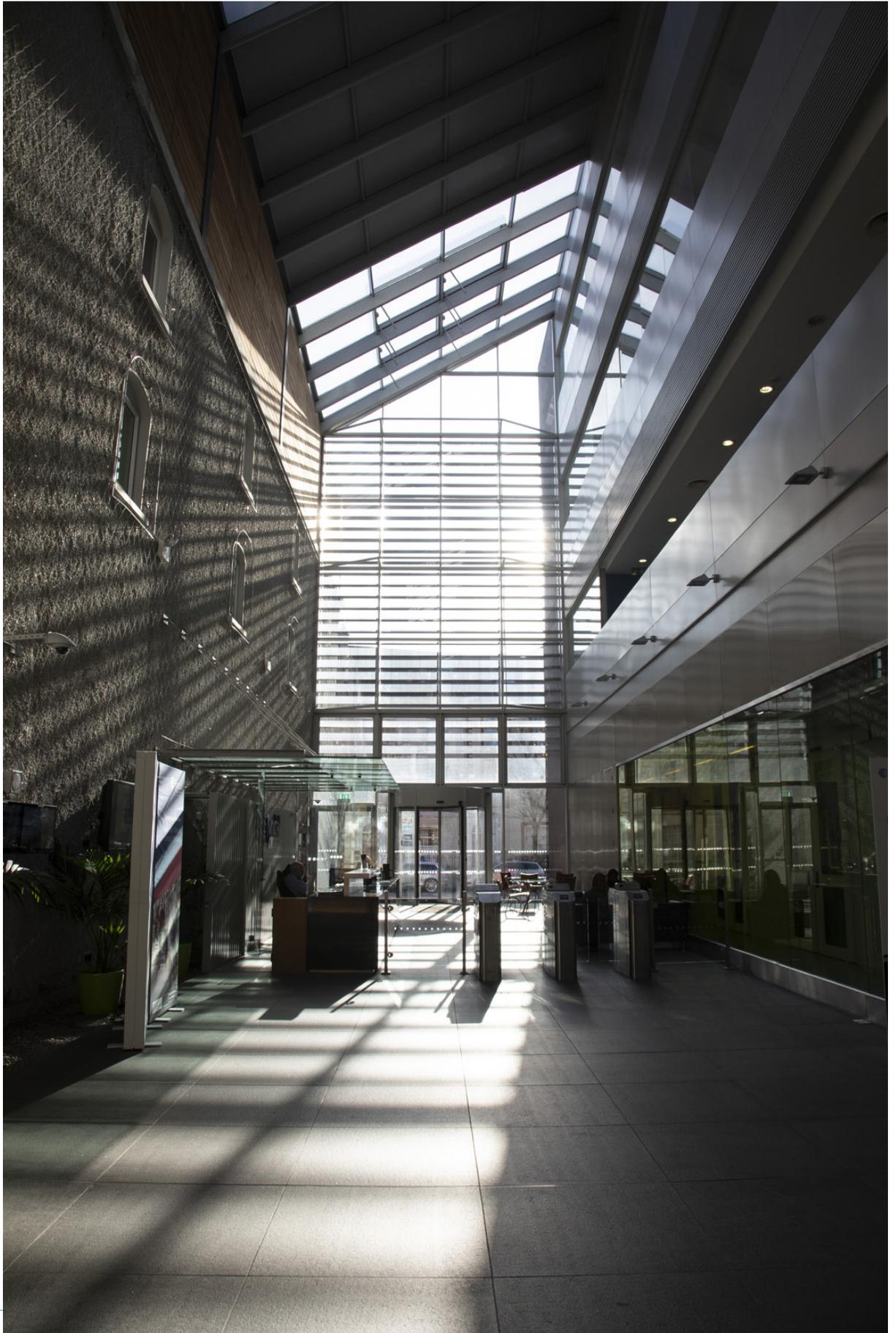
About the authors

Mike Hayes

Mike Hayes is an internationally recognized thought and technology leader in developing 'Power IoT' solutions and a supporting ecosystem, eliminating the need for battery replacement. Based in Tyndall since 2008 with 33 years of industry and academic experience in 'ICT for Energy Efficiency' research focusing on power management and system integration. He has written publications, roadmaps, participated in EU studies, presenting & chairing conferences and workshops. Coordinator of the EnABLES 'Power IoT' infrastructure project. Chairman of the US based PSMA industry association board of directors and co-founder of their energy harvesting committee. Co-founder of EnerHarv, a PSMA biennial international energy harvesting workshop in 2018.

Giorgos Fagas

Giorgos Fagas, PhD MBA, is Head of EU Programmes at Tyndall and Lead of the CMOS++ Research Theme. He engages with research organisations, technologists and policy stakeholders to establish strategic partnerships for collaborative research in Europe and internationally, and create technology roadmaps. Giorgos has been an active promoter of European research with his contributions to strategic research agendas and projects. He is also a member of the ESFRI Physical Sciences and Engineering WG, the AENEAS Scientific Council and chair of the WG on Food, Agriculture and Natural Resources in EPoSS. He has edited two reference books on ICT-Energy Concepts.

Julie Donnelly

Julie Donnelly (BSc AppSc) is a Programme Manager responsible for Access Programmes at Tyndall. From 2015-2020 she managed the €4.7m EU ASCENT programme which offers world-first access to a leading nanoelectronics infrastructure in Europe under Horizon 2020 'Access to Research Infrastructures' programme. It successfully built a network based that led to the recent launch of ASCENT+. She has also been Access Manager for EnABLES since 2018 and Programme Manager for the National Access Programme for 11 years funding 350 research projects worth > €15m. Julie has held various other roles at Tyndall since 1985 including Silicon Fabrication Manager and Technology Manager responsible for interfacing between Tyndall and its commercial customers.

Raphaël Salot

Raphaël Salot received his engineering degree in 1991 from Phelma (formerly Ecole Nationale Supérieure de Physique de Grenoble) and PhD in materials and electrochemical science. He joined CEA as a research engineer in 1996. Since 2000 he is involved in development of innovative lithium battery components for autonomous smart micro-systems. He manages the R&D activities of CEA/LETI on lithium thin film batteries and is head of laboratory. Involved in several National and European multi partners and interdisciplinary Lab2Fab collaborative projects. Coordinator of 2 European projects: FP7 – ICT project 'e-STARS' and ECSEL project 'EnSO' (65 M€ budget, more than 30 partners). Author/co-author of >30 patents and 40 publications.

Guillaume Savelli

Guillaume Savelli received a Master's degree in Engineering from Ecole Nationale Supérieure d'Ingénieurs de Caen (ENSICAEN), France (2003) specialized in microelectronics. Ph.D. degree (2007) in Electrical Engineering from the Joseph Fourier University in Grenoble. Joined CEA-Liten in 2007 and is currently in charge of thermoelectric activities. Appointed CEA expert in 2014 in nanostructured materials and thermoelectricity. Obtained HDR (Habilitation à Diriger des Recherches) from University Grenoble Alpes in 2016. Current research is dedicated to growth, characterization and integration of thin films nanostructures and development of thermoelectric devices such as µgenerators and µsensors. Member of the national scientific committee on Thermoelectrics. He has published >20 scientific papers and >30 patents.

Peter Spies

Peter Spies studied Electrical Engineering at the University of Erlangen / Germany (Dipl.-Ing. 1997). In 2010, he completed his PhD thesis on power saving in mobile communication devices. Since 1998, he is with Fraunhofer IIS, power efficient systems department working in the field of multi-standard front-ends and system simulations for communication applications. Since 2001 he is group manager of the "Integrated Energy Supplies" group where he is doing research and design on power and battery management, energy transmission and energy harvesting. Since 2018 his group joined the department "Self-powered Radio Systems". Coordinator of the business field "IoT-Systems" at Fraunhofer IIS in Nuremberg.

Gerd vom Boegel

Gerd vom Boegel received the Diploma degree in electrical engineering from the University Duisburg in 1992. He joined the Fraunhofer Institute for Microelectronic Circuits and Systems in Duisburg and has established the business area sensor transponder. In 1999 he received the Dr.-Ing. degree from the University Duisburg. At present he is responsible for the business unit "Industry" at Fraunhofer Institute IMS. His main research topic is in the area of IoT, energy harvesting, sensor transponder systems and RFID in metal environments.

Mario Konijnenburg

Mario Konijnenburg (M'08) received the M.S. degree in electrical engineering from Delft University of Technology in The Netherlands in 1993. A Ph.D. degree was received from Delft University of Technology in 1999 on Automatic Test Pattern Generation for Sequential Circuits. He joined Philips Research / NXP Semiconductors and worked on methodologies to improve testability of designs. Currently he is system/chip architect at imec in Eindhoven, The Netherlands where he works on development of ultra-low power designs for bio-medical applications.

David Stenzel

David Stenzel received the Master's degree in Material Science and Engineering at the Karlsruhe Institute of Technology (KIT). Currently he is a Ph.D. student at the Technical University of Darmstadt and the Institute of Nanotechnology, KIT. His research focuses on the synthesis and characterisation of new materials for Li-ion batteries and further electrochemical applications. He is involved in the NanoMat nano competence centre, a local coordinator for the EnABLES 'Power IoT' infrastructure project and works in the technology transfer for the POLiS Cluster of Excellence.

Aldo Romani

Aldo Romani is currently an Associate Professor of Electronics at the University of Bologna, Campus of Cesena, Italy. He has been working on energy harvesting systems and circuits for micropower management for over 10 years. He has also been involved with different types of sensor interfaces and systems, and applications of piezoelectric transducers. He participated or is participating to several national and European research programmes. He has authored or co-authored more than 90 international scientific publications. Dr. Romani was a co-recipient of the 2004 Jan Van Vessem Award of the IEEE International Solid-State Circuits Conference.

Claudio Gerbaldi

Claudio Gerbaldi is Full Professor of Chemistry at the Politecnico di Torino (IT). Leader of the Group for Applied Materials and Electrochemistry (GAME-Lab), working on development of advanced electrochemical energy storage/conversion systems, with effective connections with industry and EU (6 funded EU projects). Author of >150 articles (>6500 citations, h-index 51), 5 international patents, 6 book chapters. Visiting scientist at MIT (US) and the Cambridge Graphene Centre (UK) and participated in >80 conferences (>120 presentations, 12 as invited/keynote). Among others, he received the International "Roberto Piontelli" Award delivered by the President of the Italian Republic, for outstanding contributions in the field of electrochemistry for energy-related applications.
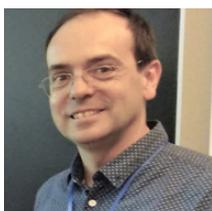
Francesco Cottone

Francesco Cottone is currently a researcher and assistant professor at Department of Physics and Geology at University of Perugia (Italy). Since his PhD in Physics in 2008, he conducts research on nonlinear harvesting systems, starting at Stokes Institute, University of Limerick (Ireland). He was awarded a Marie Curie European Fellowship at Université de Paris-Est (France). Since 2013, he has been the principal investigator and responsible of European funded projects related to energy harvesting and IoT (NanoPower, ICT Energy, PROTEUS). In 2015, Francesco was awarded best researcher prize in honour of professor Borromeo. He is a member of scientific committees of international conferences and has a record of >90 refereed publications.

Alex Weddell

Alex Weddell is a Lecturer (Assistant Professor) with the Centre for Internet of Things and Pervasive Systems, University of Southampton, and Technical Manager of the Arm-ECS Research Centre, an award-winning collaboration between Southampton and Arm Research. Co-investigator on three projects funded by EPSRC, EU Horizon 2020 and Clean Sky 2, and has over 15 years' experience in energy harvesting systems. He has published around 80 peer-reviewed papers in the area and holds three patents. His main research focus is in the areas of energy harvesting and energy management for future Internet of Things devices.

Coordinator

Tyndall
National Institute
Institiúid Náisiúnta

Our partners

leti
cea tech

liten
cea tech

Fraunhofer
IIS

Fraunhofer
IMS

imec

KIT
Karlsruher Institut für Technologie

POLITECNICO
DI TORINO

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

UNIVERSITÀ DEGLI STUDI DI PERUGIA
DAL 1308 COSTRUIAMO IL FUTURO

UNIVERSITY OF
Southampton

EnABLES

Coordinator

Tyndall
National Institute
Institiúid Náisiúnta

Our partners

leti
cea tech

liten
cea tech

Fraunhofer
IIS

Fraunhofer
IMS

imec

KIT
Karlsruher Institut für Technologie

POLITECNICO
DI TORINO

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

UNIVERSITÀ DEGLI STUDI DI PERUGIA

UNIVERSITY OF
Southampton

EnABLES

Mike Hayes,
EnABLES Project Coordinator,
Tyndall National Institute,
Lee Maltings, Dyke Parade,
T12R5CP
Cork, Ireland.

michael.hayes@tyndall.ie
www.enables-project.eu

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh