4E Electronic Devices & Networks Annex
EDNA

Energy Harvesting Technologies for IoT Edge Devices

JULY 2018

Energy Efficient End-use Equipment
International Energy Agency

4E is the Energy Efficient End-Use Equipment Technology Collaboration Programme, established by the International Energy Agency (IEA) in 2008 to support governments in co-ordinating effective energy efficiency policies. Twelve countries have joined together under the 4E platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However 4E is more than a forum for sharing information – it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Participants find that is not only an efficient use of available funds, but results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions.

Current members of 4E are: Australia, Austria, Canada, China, Denmark, France, Japan, Korea, Netherlands, Switzerland, Sweden, UK and USA.

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Electronic Devices & Networks Annex
EDNA

Network connected devices, including the Internet of Things, are growing rapidly and offer enormous opportunities for improved energy management. At the same time, there is a responsibility to ensure that these devices use a minimal amount of energy to stay connected. 4E's Electronic Devices and Networks Annex (EDNA) works to align government policies in this area and keep participating countries informed as markets for network connected devices develop.

Further information on EDNA is available at: **http://edna.iea-4e.org**

This report is authored by Fatih Ünlü and Lukas Wawrla of Helbling Technik AG and Adriana Díaz of ECODESIGN company.

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Executive Summary

In 2016 the Electronic Devices and Networks Annex (EDNA) published the report "Energy Efficiency of the Internet of Things (IoT)". The report highlighted the predicted substantial increase in usage of IoT edge devices, in numerous applications such as smart roads, smart street lighting, smart appliances, home automation and smart lighting. Many of these IoT applications utilise battery-powered edge devices whose batteries have a limited useful life.

The objective of this EDNA study is to explore the potential to utilize Energy Harvesting Technologies (EHT) to reduce the need for, or even eliminate, the batteries used in IoT edge devices. In this context, relevant edge devices include end-user equipment and appliances that can be connected to networks and interact with the network and/or with other devices. Examples include sensors for temperature, light, smoke, activity tracking; actuators for windows and also thermostats.

This report discusses the elements of an energy harvesting system, and the possible energy sources and quantities of energy which can be harvested from light, thermal energy, radio frequency electromagnetic radiation or induction, and kinetic energy (motion, vibration, rotation, and linear movement). Examples of available energy harvesting technologies are presented such as thermoelectric generators, piezoelectric elements, electromagnetic generators, triboelectric generators, antenna/rectenna, photovoltaic cells and electrostatic motors.

This report aims to provide an overview on the state of development of EHT in relation to selected areas of application in buildings (e.g., smart homes, factories and offices); in health (for monitoring), for infrastructure (e.g., smart logistics and mobility); and in the environment (e.g., smart agriculture and environmental monitoring). An important use of EHT is in automation of smart homes and buildings, because the copper wiring (for sensors and actuators) can be reduced, as well as reducing materials, installation and maintenance costs. Currently industry is developing EHT to better and more efficiently bridge the gap from 10 µWatt to 1 Watt, because IoT devices are predominantly found in this power range. The intermittent power demand of the loads might also require the supply of additional energy to compensate for insufficient harvested energy during specific times, and/or the storage of excess harvested energy for later use. Storage components such as supercapacitors - the main types and their use in relation to EHT - are also discussed in this report.

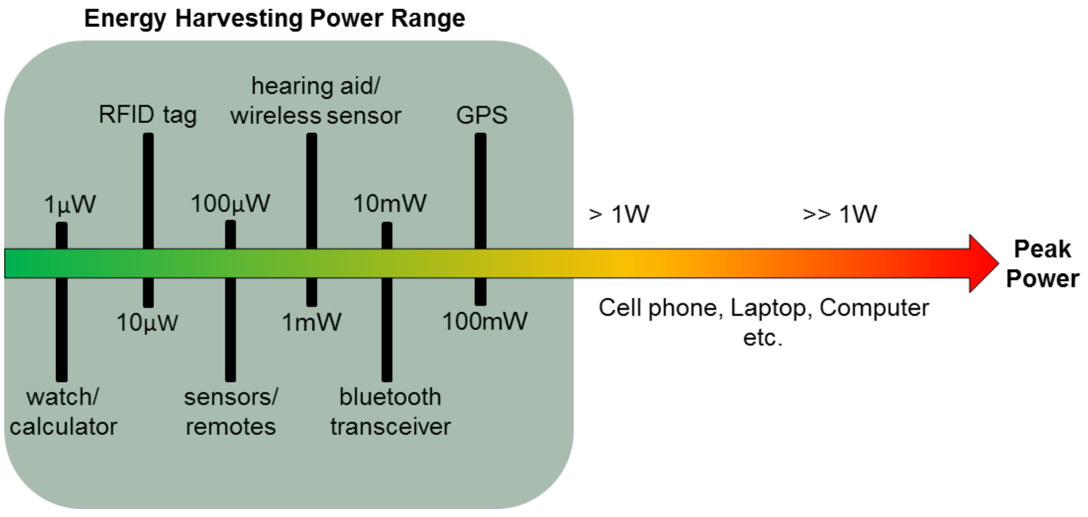

Figure 1: Power consumption overview of devices incl. energy harvesting power range.

For this study, a sample of battery-powered IoT edge devices were chosen and power measurements conducted. Their energy use profile was also examined and the potential for implementation of EHT explored. The devices selected were: radiator thermostat, door/window contact, smoke/CO alarm, wireless thermometer, anti-theft alarm, tracking device and a plant pot with multiple sensors/actuator.

The results of the measurements on these products indicated that the energy consumption was in the expected range, for both communication spikes and other functions. The intermittent energy demand between wireless transmissions is in the high µW to mW range, and buzzers and actuators have the highest energy demand. Suitable EHTs where considered for these devices based on these results. As an example, the anti-theft alarm is suited for implementing vibrational energy harvesting for the sensor node (with low power acceleration/displacement sensor), combined with energy storage for powering the alarm buzzer. For the other products considered in this study, the energy harvester provides enough power to operate each product's sensor. However, the communication module, buzzers and the water pump have higher power demands, for which the use of supplementary energy storage would be necessary. The report also discusses the use of low energy communication protocols and the adaptation of use profile parameters (e.g., reception/transmission and data processing) for the EHT implementation in edge devices.

The development of EHT takes time since it involves fundamental research, and the research cost may be an obstacle to industry development and commercialisation. On the other hand, there are also potential benefits in deploying EHT for selected applications. In this sense, the report provides examples of different policy options that energy efficiency policy makers could consider to promote EHT, such as provision of information and education, inclusion of criteria for EHT in building codes and product standards, and support for research, development, and deployment (RD&D). This report concludes with recommendations for further consideration and discussion by EDNA.

1. Introduction

1.1. Background

The Electronic Devices and Networks Annex (EDNA) is an annex of the International Energy Agency's (IEA) "Efficient Electrical End-Use Equipment (4E)" IEA Technology Collaboration Programme. EDNA focuses on "network connected devices" i.e. devices connected to a communications network, for example a household Wi-Fi network. EDNA aims to ensure that the next generation of such devices use electricity as efficiently as possible. Also, network connected devices can be controlled, and this offers enormous opportunities for energy management. At the same time, there is a responsibility to ensure that these devices use a minimal amount of energy to stay connected.[1]

1.2. What is IoT

One very relevant group of connected devices are the so-called IoT edge devices. The abbreviation IoT stands for "Internet of Things". This term describes the idea of connecting people, animals, everyday objects and sensors to a communication network and, thus, placing them at the "edge" of the network.

1.3. IoT Edge Devices

"The edge of the IoT is where the action is. It includes a wide array of sensors, actuators, and devices - those system end-points that interact with and communicate real-time data from smart products and services [1]". Thus, edge devices include end-user equipment and appliances that can be *connected* to networks and *interact* with the network and/or with other devices. These interactions can include issuing commands, activating actuators, or transmitting sensor data. For example a light and humidity sensor can activate a water pump to irrigate a field if the soil humidity became too low in a period of sunny rainless days. The connection to the network is either established with a cable connection or with a wireless radio-frequency protocol to a smartphone, gateway or a router. The type of wireless connection can vary from Wi-Fi, Bluetooth mobile internet to many others. Some devices can also include multiple forms of wireless connection.

1.4. Current Situation

The EDNA Task 2 - Energy Efficiency of the Internet of Things - reports that, by 2022, there will be around 50 billion devices connected to the internet [2]. Furthermore, it is estimated that 200 things per person could be connected, potentially leading to several hundred billion devices.

Many IoT edge devices are battery powered, particularly actuators and sensors which are generally placed in decentralized locations. The corresponding energy use and physical waste related to batteries are considerable. One rough estimate yields a figure of more than 23 billion battery powered IoT devices in 2025.

The elimination of batteries as an inefficient energy source is important and there are several measures which address this. Additionally, it is known that the materials needed for battery production are becoming scarcer, and the challenges associated with the waste management at the end of life of batteries are also well documented. Energy Harvesting Technologies represent a key solution to this problem [2].

The emerging market of EHT is already well developed in particular areas, and new technologies are entering the market all the time. But often these technologies are not well known by Governments or IoT manufacturers. Therefore, this work serves to make an international technology assessment for policy makers (especially in 4E),

[1] https://edna.iea-4e.org/

presenting an overview of the existing and emerging EHTs, as well as assessing their relevance and potential in relation to deployment in IoT edge devices.

1.5. Goal and Scope of Project

The overall goal of the study is to make an international survey of existing and emerging Energy Harvesting Technologies (EHT) and investigate their potential to be used in IoT edge devices. Using desk research, relevant international publications and projects are identified. Not only EHT used in IoT devices are identified, but also EHTs which are used in other segments (for example wearables) and which have the potential to be well incorporated into IoT edge devices are studied.

Firstly, an overview of existing and emerging EHT is provided, including the existing usage in particular segments and the potential of usage in IoT edge devices. This includes a rough estimation of the energy required by an individual IoT edge device, and the potential for energy production using different EHTs. Environmental variables must also be included, as EHTs often need specific conditions to operate (for example temperature differences).

The report gives information about the actual status of EHT, where it might be heading, and the potential hurdles. It is designed to inform policy maker of what is occurring in this area. On the other hand, clear messages to IoT manufacturers and their associations are intended to inspire them to use EHT. Finally, the results should also inspire industry to invest in new and promising EHT and give Governments justification to be active in the EHT area.

The overall goal of this study is to make an international survey of existing and emerging Energy Harvesting Technologies (EHT). In addition, existing devices and applications, whose energy production is already based on EHT are investigated and categorized in groups. Among others, EHT with high potential for incorporation in future IoT devices are also studied. Furthermore, current research projects, e.g. in Switzerland, Japan etc., were tracked and the corresponding researchers were contacted. The study includes a rough estimation of the required energy of IoT devices powered by battery, and attempts to clarify whether batteries can be replaced with matching EHT. The boundary conditions for the implementation of EHT in existing battery powered IoT devices are analysed and the possibility of application is examined. Potential benefits and hurdles for EHT are discussed and related to the industry.

1.6. Project Setup

The project is divided into five work packages. The focus is different for each project phase. Helbling Technik AG (Helbling) was supported in this work by the ECODESIGN company engineering & management consultancy GmbH (ECO) from Vienna, Austria. ECO is specialized in formulating policy briefs for politicians and government. Thereby, ECO is an excellent partner for this EDNA project and they are completely integrated in correspondingly tasks. The numerous responsibilities, split between Helbling and ECO, are illustrated in the following section.

Work package 1: Identifying existing and emerging EHT and EHT-using applications

- Identify existing devices and applications with implemented EHT
- Search upcoming EHT applications not fully developed
- Identify emerging, existing and promising EHT
- List and contact potential industry partners and research experts
- Get in contact with EDNA delegates

Work package 2: Estimation of Energy needed by IoT-devices

- Value and select different IoT edge devices with battery
- Purchase IoT edge devices with battery or hybrid technology
- Identify operation scenarios for selected devices (ECO)
- Measure/analyse battery consumption

Work package 3: EHT in IoT devices

- Most promising battery powered IoT edge devices from WP2 are selected
- Verify if it is possible to replace battery with EHT
- Assess feasible EHT as per "Standby power consumption" (EDNA Task) threshold (ECO)
- Assess industrialization effort for selected EHTs (goal: use of such EHTs for specific products)

Work package 4: Conclusions

- Draw overall conclusion of WP 1,2,3 incl. Feedback from EDNA delegates congress (together with ECO)
- Prepare concept for policy makers (ECO)

Work package 5: Report and Presentation

- Coordinate results and corrections with ECO
- Finalize report and presentations

2. Prioritization

IoT edge devices occur in many different environments and the use and impact varies from area to area. In addition to the "Energy Efficiency in Internet of Things" report [2], applications for IoT edge devices are organized in several categories, such as:

- Smart Home
- Smart Factory
- Smart Office
- Smart Health
- Smart Retail
- Smart Logistics
- Smart Mobility
- Smart Agriculture
- Smart Environment Monitoring
- Smart Law Enforcement/Civil service
- Smart Grid

A detailed overview with IoT applications is provided with Table 1. The focus was placed on categories in which IoT edge devices are used and where an implementation with energy harvesting as external energy source could be a viable alternative energy source and ecologically worthwhile (these are highlighted in green). Devices with a mains connection and from application areas under the scope of other EDNA tasks are not in our focus. The Data gathering about the IoT application areas, especially highlighting those areas with EHT potential, are derived from previous EDNA reports, desk research, industry and academia contacts.

In general, the (IoT edge) devices which are of interest to us are mostly sensors and actuators:

- Sensors for temperature, presence, light, smoke, CO, CO_2.
- Activity and sleep tracking sensors.
- Home automation actuators e.g., for windows, thermostats, water pump, …

Some categories are overlapping; therefore, categories were merged as follows:

- Smart Building (Smart Home, Smart Factory, Smart Office)
- Smart Health
- Smart Infrastructure (Smart Logistics, Smart Mobility)
- Smart Environment (Smart Agriculture, Smart Environment Monitoring)
- Smart Military/Civil service

The 2016 Task II report [2] about IoT presented relevant areas for IoT applications. These application categories were considered in Task VI to focus on:

- Smart Building (Smart Home, Smart Factory, Smart Office)
- Smart Health
- Smart Infrastructure (Smart Logistics, Smart Mobility)
- Smart Environment (Smart Agriculture, Smart Environment Monitoring)
- Smart Grid

Other areas are either to small regarding user base or are already in the scope of other Tasks or like Smart Retail are not in the main scope of the task.

Table 1: IoT applications with/without EHT. In green are the application areas which are of interest for us.

Application Area	Application Area	Application	Edge Device	Power Source	Energy source for EH
Smart Building	Smart Home	smart lightning	smart LED bulb	mains	
			gateway, hub	Mains, POE	
			smart light switches	battery, EH	vibrations (pressure)
		Home automation	battery/EH powered sensors (e.g. smoke detector, door/window, temp., humidity, thermostat)	battery, EH	light, thermal
			mains connected sensors (e.g. light buttons, control system etc.)	mains	
			camera	mains	
			gateway	mains	
			actuators	mains	
	Smart Office	office automation (HVAC, lighting)	sensors (temperature, presence, light, smoke, CO, CO_2)	mains, battery EH	light, thermal
			actuators (lights, blinds etc.)	mains	
			gateway	mains	
			server	mains	
		access control	badge	passive, battery	
			reader (door, time reporting, etc.)	mains	

Application Area	Application Area	Application	Edge Device	Power Source	Energy source for EH
		intrusion detection	camera	mains	
			door / window sensors	mains, battery EH	light, vibrations
			motion sensors	mains, battery EH	light
		fire detection	smoke detector / gas sensor	battery, EH	light, thermal
	Smart Factory	asset tracking	RFID tag	passive, battery EH	light, thermal, RF
		inventory management	RFID tag	passive, battery EH	light, thermal, RF
		machine wear monitoring	dedicated sensors	mains	
		machine diagnostics	dedicated sensors	mains	
		maintenance conditions	dedicated sensors	mains, battery EH	
		smart pipelines	sensors (thermal, pressure, humidity...)	battery, EH	
		machine remote control	machine	mains	
Smart Health	**Smart Health**	physical activity monitoring	activity tracker	battery, EH	vibrations, thermal, light
		weight monitoring	smart body scale	rech. battery, EH	vibrations, thermal, light
		sleep monitoring	bed-side device	mains	
			sleep sensor / activity tracker	rech. battery, EH	vibrations, thermal

Application Area	Application Area	Application	Edge Device	Power Source	Energy source for EH
		nutrition monitoring	smart cup	rech. battery, EH	thermal
			smart clothes	rech. battery, EH	vibrations, thermal, light, RF
		human monitoring	GPS tracker / beacons	rech. battery, EH	vibrations, thermal, light
		long term monitoring / preventive care	body-core-temp sensors	rech. battery, EH	thermal
		cardiologic health	pacemaker	battery, EH	vibrations
		dental health	electrical toothbrush	rech. battery, EH	light, RF, electromagnetic
		emergency notification	emergency tag (watch, pushbutton)	rech. battery, EH	vibrations, thermal, light
		fall detection	fall sensor	battery, EH	vibrations, thermal, light
			gateway (landline or mobile network)	mains	
		biocompatible sensor	smart pills	battery, EH	Thermal, redox react.
Smart Infrastructure	**Smart Mobility**	breakdown/emergency notification	GPS / Cellular in car	on-board, rech. battery	
		road pricing	transceiver in car	on-board, rech. battery, EH	vibrations, solar
		smart roads	sensor networks in roads	battery, EH	vibrations, thermal, RF
			smart road lights	Mains,battery, EH,	vibrations, solar
			energy gaining roads/sport fields	EH	vibrations
		traffic congestion monitoring	GPS / Cellular in car	on-board, rech. battery	

Application Area	Application Area	Application	Edge Device	Power Source	Energy source for EH
		car-to-car communication	various devices in car	on-board	
		car-to-infrastructure communication	various devices in car	on-board, battery, EH	vibrations, solar
		smart tunnels/bridges	dedicated sensors (pressure, humidity, temperature etc.)	mains, battery, EH	vibrations, thermal
	Smart Logistics	product tracking	RFID tag	passive, battery, EH	vibrations, thermal, light, RF
		quality of storage condition monitoring	dedicated sensors	battery, EH	vibrations, thermal, light, RF
		quality of shipment conditions monitoring	dedicated sensors	battery, EH	vibrations, thermal, light, RF
		fleet racking	GPS	on-board, rech. battery	
			maintenance conditions	battery, EH	vibrations, thermal, light
		waste management	waste containers with filling sensors	battery, EH	light, vibrations
	Smart Retail	product tracking	RFID tag	passive, battery, EH	vibrations, RF, thermal, light
		automatic shop check out	RFID tag	passive, battery, EH	vibrations, RF, thermal, light
		smart vending machines	vending machine	mains	
			smart phone / pad	rech. battery	

Application Area	Application Area	Application	Edge Device	Power Source	Energy source for EH
Smart Environment	Smart Agriculture	animal tracking	RDID tags, GPS transceiver	passive, battery, EH	vibrations, solar
		irrigation monitoring	dedicated sensors	battery, EH	
		pest monitoring	dedicated sensors	battery, EH	
		smart gardening	dedicated sensors	battery, EH	
	Smart Environment Monitoring	water quality monitoring	dedicated sensors	battery, EH	
		flood monitoring	dedicated sensors	battery, EH	
		forest fire detection	dedicated sensors	battery, EH	
		landslide / avalanche detection	dedicated sensors	battery, EH	
		earthquake early detection	dedicated sensors	battery, EH	
		glacier monitoring	dedicated sensors	solar, thermal	
Smart Law Enforcement/ Civil service	Smart Law Enforcement/ Civil service	charging consumer electronics	smart charger	battery, EH	
		location monitoring	crowd GPS / beacons	battery, EH	
		safety monitoring	health conditions of soldier	battery, EH	
Smart Grid	Smart Grid				

2.1. Aspects, that are out of scope

The following topics are out of scope: The following list contains items that are not part of the approached work packages. A comprehensive ratio is provided for each of them.

- **Mains connected devices**
  The standby energy consumption of mains connected IoT devices, because this topic has been covered by the 4E EDNA Task II “Energy Efficiency of the Internet of Things” [2].
- **Traditional network-enable devices**
  Laptops, smartphones, tablets, game consoles, smart TVs and transmission equipment are out of scope due to the fact that their energy consumption are too high for energy harvesting applications (see Figure 4) and they have been covered by other work [3].
- **Large size**
  Energy Harvesting Techniques which do not fulfil the size requirements for IoT edge devices, such as turbines used in hydroelectric power plants or windmills in big wind parks etc.
- **Chemical/biological energy source**
  These energy sources for IoT edge devices are not discussed because the potential of implementation is very low (not enough space, rarely available energy source in IoT environment). The effort for and use of chemicals in refuelling micro fuel cells runs counter to the idea in replacing batteries.
- **Smart Grid application area**
  This topic has been investigated within the 4E EDNA task “Smart Metering Infrastructure and Energy Monitoring Systems”.
- **Big Data and Cloud Computing**
  These two topics have been considered out of scope because the focus of the report is placed on the potential implementation of EHT into IoT devices and not how to manage the data flow (resp. data overflow).

3. Energy Harvesting

3.1. What is Energy Harvesting?

Energy harvesting, also known as energy scavenging or power harvesting, is the process by which energy is derived from external sources. The energy source for energy harvesters is called "ambient energy", which is present as ambient background and freely available. The main task of an energy harvesting device is converting the captured ambient energy into electrical energy and in a next step power consumer electronics, wireless sensor nodes, implantable biosensors, military equipment and many more [4] [5]. There are many different energy sources that can be used for the conversion, such as:

- Light energy (solar energy form sunlight (outdoor) or lamps (indoor)) [6] [7]
- Thermal energy (human body, industry) [8] [9]
- Radio frequency energy (electromagnetic spectrum, antennas) [10]
- Kinetic energy (motion, vibration, rotation, linear movement) [11] [12] [13] [14][2].
- Chemical/biological energy (osmose, diffusion, radioisotopes, redox reactions)
- Atmospheric energy (gravity changes, pressure changes etc.)
- Hydro energy (kinetic energy from water)

However, not all of them are suitable for energy harvesting application in IoT devices. We will focus on technologies which generate directly through an appropriate transducer an electrical current. Section "Requirements for Energy Harvester in IoT" provides an overview of requirements to be met for devices which can harvest energy.

3.2. Energy Harvesting Technology

Energy Harvesting Technologies (EHT) can convert ambient energy, such as solar energy, thermal, vibrational or RF energy into usable electrical energy. As illustrated in

Figure 2, a complete energy harvesting system comprises in its simplest form three main components

1. A transducer,
2. An interface circuit (architecture with or without energy storage)
3. A load

The use-case and the required energy supply determine which EHT and additional electronics must be implemented into a device. According to many researchers [15], EHT are a very attractive technique for a wide variety of self-powered microsystems, for instance Internet of Things (IoT) edge devices.

[2] Most of small size technologies harvesting kinetic energy are vibrational based. Therefore, we will use "vibrational" as the main categorization for kinetic based EHTs and indicate otherwise in special cases.

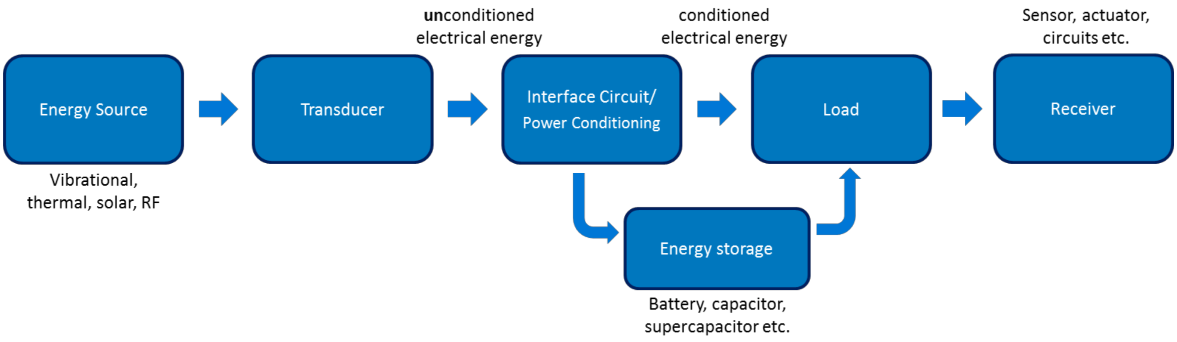

Figure 2: Block diagram of an energy harvesting system. Adapted from [9] [10] [16]

Yuan Rao et al. from the University of Florida describes EHTs as promising emerging technologies to achieve autonomous, self-renewable and maintenance free operation of wireless electronic devices [9].

The transducer is responsible for the converting the energy harvested from the ambient source (mechanical, thermal, solar, etc.) to the electrical domain. Conventionally, the transducer is often called "energy harvester". Furthermore, the interface circuit serves to extract a maximum amount of energy from the transducer [4]. In addition, it makes the energy feasible to the load by various adjustments such as voltage rectification, voltage regulation and other power management functions [17]. The load may comprise power consuming electronic devices (circuits, sensors, actuators etc.) and/or energy storage elements (batteries, capacitors, supercapacitors etc.) as depicted in Figure 2. To avoid a startup problem of a complete energy harvesting system an energy storage is implemented into the circuit, which bridges the energy supply in case of a long idle time interval between two harvesting cycles.

Section 3.4 provides an overview of existing, emerging EHT and EHT, which are currently under development and probably relevant for future applications. Furthermore, in chapter 4 existing devices and appliances are discussed, which already regulate their energy supply with EHT. The focus is placed on IoT edge devices. Nonetheless, EHT which are used in other segments, for example wearables or smart handhelds, are also considered.

3.3. Requirements for Energy Harvester in IoT

Energy harvester for IoT edge devices should fulfil requirements, such as power range, costs and dimensions. The available energy sources play also a major role.

3.3.1. Power

Intrinsically, the energy harvester should scavenge at least milliwatts of power from the environment of the IoT edge device. In Figure 3 an overview of different EHT with their generated intermittent power. The generated energy can cover multiple orders of magnitude.

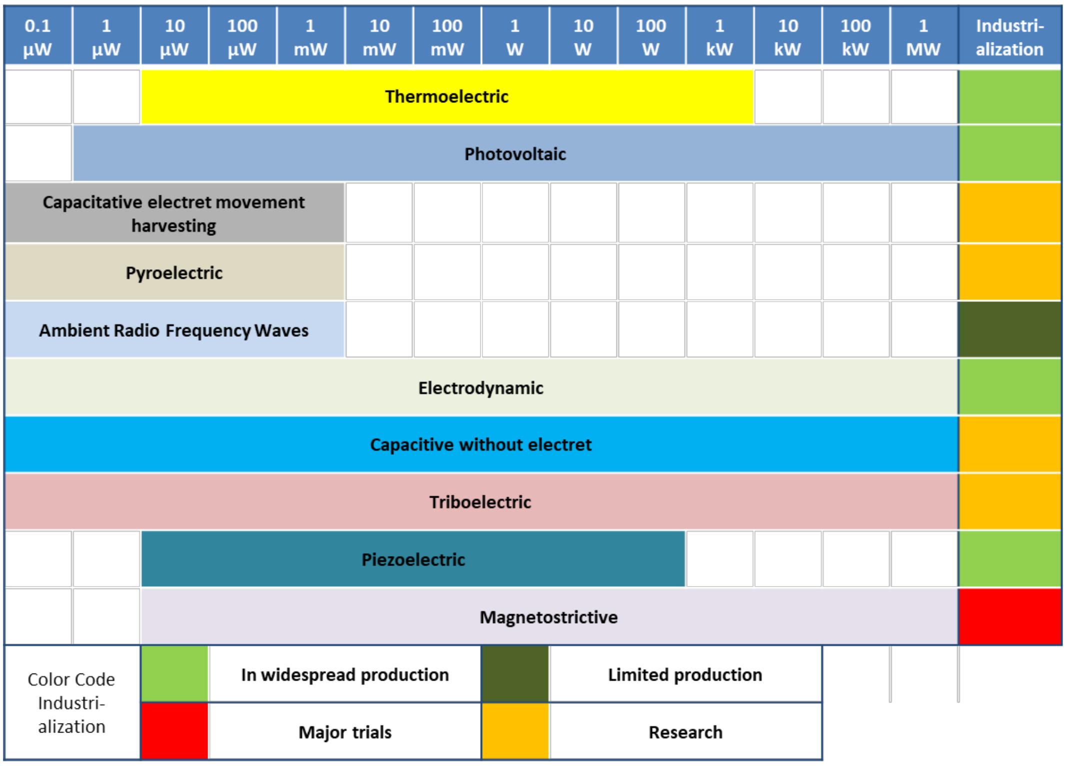

Figure 3: State of EH technologies and their generated intermittent power [18].

The relevant range for IoT devices and sensors are between 0.1 µW and 1 W. As illustrated in Figure 4, the feasible power generation range of an energy harvesting device (photovoltaic cell) with a manageable size is up to 500 mW. This is because the power consumption of IoT edge devices is around 100µW/cm^2. Since energy supply and demand may come at different times, in practice a temporary energy buffer (e.g. supercapacitor) and power management electronics are necessary to effectively deliver the energy from the harvester to the IoT edge device.

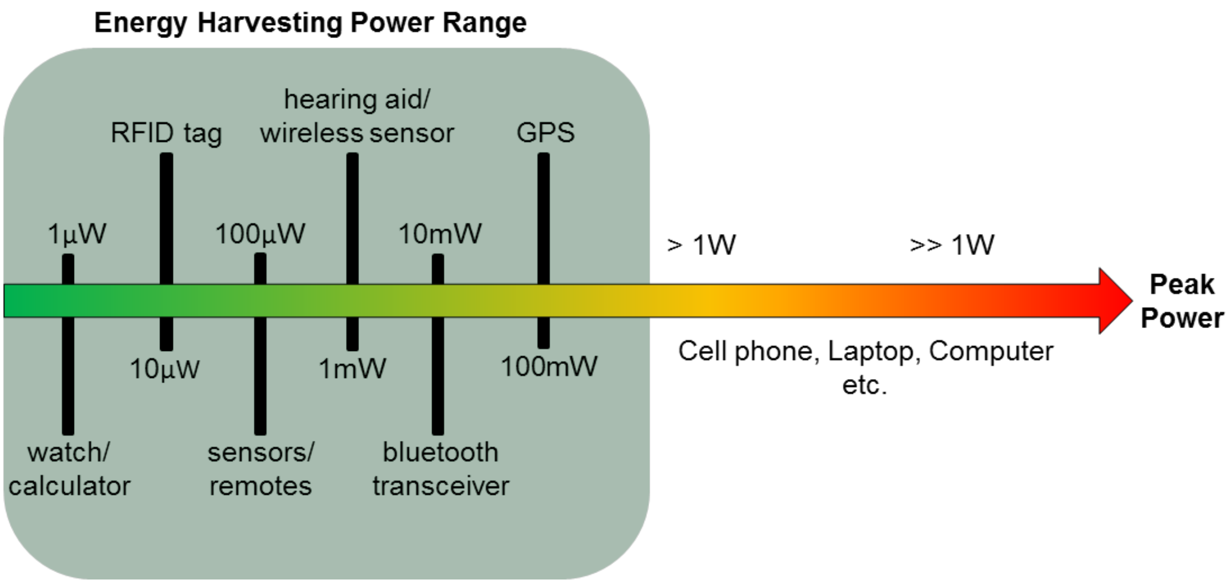

Figure 4: Power consumption overview of devices incl. energy harvesting power range. Adapted from [19], [20], [21].

3.3.2. Costs

It can be generally assumed that battery driven IoT edge devices are cost sensitive in their production. Integrating an EHT into the device design will increase the costs. Batteries are a mass produced cheap commodity and EHT are not. The costs include beside the component costs the redevelopment costs of the device since just adding an EHT on top of the device is often not feasible.

Figure 5: Process for developing self-powered sensor nodes. Adapted from [22].

Figure 5 presents one approach to the design process for a self-powered device. However, not all manufacturers have the resources to follow this approach. As IoT becomes more and more ubiquitous, there will be edge devices from different manufacturers which perform the same *simple* tasks and use similar or even the same systems-on-a-chips (SoC). This would increase the possibility to standardize the appropriate EHT for this kind of IoT edge devices.

Secondly, the manufacturers are already passing the running costs, e.g. battery replacements at least every half a year, to the user. Removing these costs and increasing the user friendliness of the device by eliminating maintenance tasks could offset higher sales prices.

3.3.3. Size

With the progress in integrated circuit design and being able to integrate more functions into one chip, e.g. SoC design, the size of the IoT edge device is no longer the bottleneck of the system. The battery, which normally powers such devices, guarantees in optimal cases to have a 1-year life time and often dominates size and weight of the system. The energy harvester, as the alternative to the battery, should ideally not take up more space than the previous energy source. Depending on the applications, the size of the scavenger can vary. Generally, energy harvester should not be larger than **10 cm^3**, which is already quite big. In addition, scalability of the energy harvester with the size of the IoT edge device would be ideal. Table 2 provides an overview of power densities of some ambient energy sources of existing EHT.

Table 2: Overview of Energy Sources [10]

	Solar Energy	Thermal Energy	Ambient RF Energy	Piezoelectric Energy	
				Vibration	Push Button
Power Density	100 mW/cm^2	60 µW/cm^2	0.0002 - 1 µW/cm^2	200 µW/cm^2	50 µJ/N
Output	0.5 – 1 V	-	3 – 4 V	10 – 25 V	0.1 – 10 kV

Table 3 Power Estimation of various Energy Harvesting Technologies [23]

Energy Harvesting Technology	Conditions/Device	Power Range	Volume in cm³	Comments on source	Use
Thermo-electric Generator (TEG)	Δ 1 – 20 K	µW range	-	-	Power wireless sensor
	Δ 20 – 50 K	mW range	-	-	Light LEDs, power small motor
	Δ 50 – 100 K	W range	-	-	Charge phone
Indoor Photovoltaic[3] (PV)	150 lux	0.1 mW	-	This also depends strongly on the type of light source (LEDs, fluorescent, etc. …)	Power wireless sensor
	300 lux	0.3 mW	-		
	1'000 lux	1 mW	-		
Outdoor PV	> 3'500 lux	100 mW/cm²	-	-	Charge phone
Vibrational Energy Harvesting (VEH)	Parametric Prototype	78.9 mW	126	Electrodynamic	Light LEDs, power small motor
	Direct Prototype	64.8 mW	126	Electrodynamic	
	Microstrain	30 mW	66	Piezoelectric	
	Perpetuum	45 mW	135	Electrodynamic	
	Microgen	0.12 mW	0.83	MEMS Piezoelectric	Power wireless sensor
	Omron	0.14 mW	73	Electret	
	Imec	0.085 mW	0.15	MEMS Piezoelectric	

3.4. Ambient Energy Sources

There is variety of ambient energy sources as presented in Figure 6. The corresponding harvesting technology is also depicted. The EHT on which this report is focusing are highlighted in green. These technologies are suitable for IoT devices either from their size or their general simplicity of the corresponding transducer in generating "directly" an electrical current or from energy sources, which are assumptive to be available in IoT edge devices environments.

[3] Panasonic AM-1815CA, V_{oc}=4.9V, size 58.1 mm x 48,6 mm x 1.1 mm

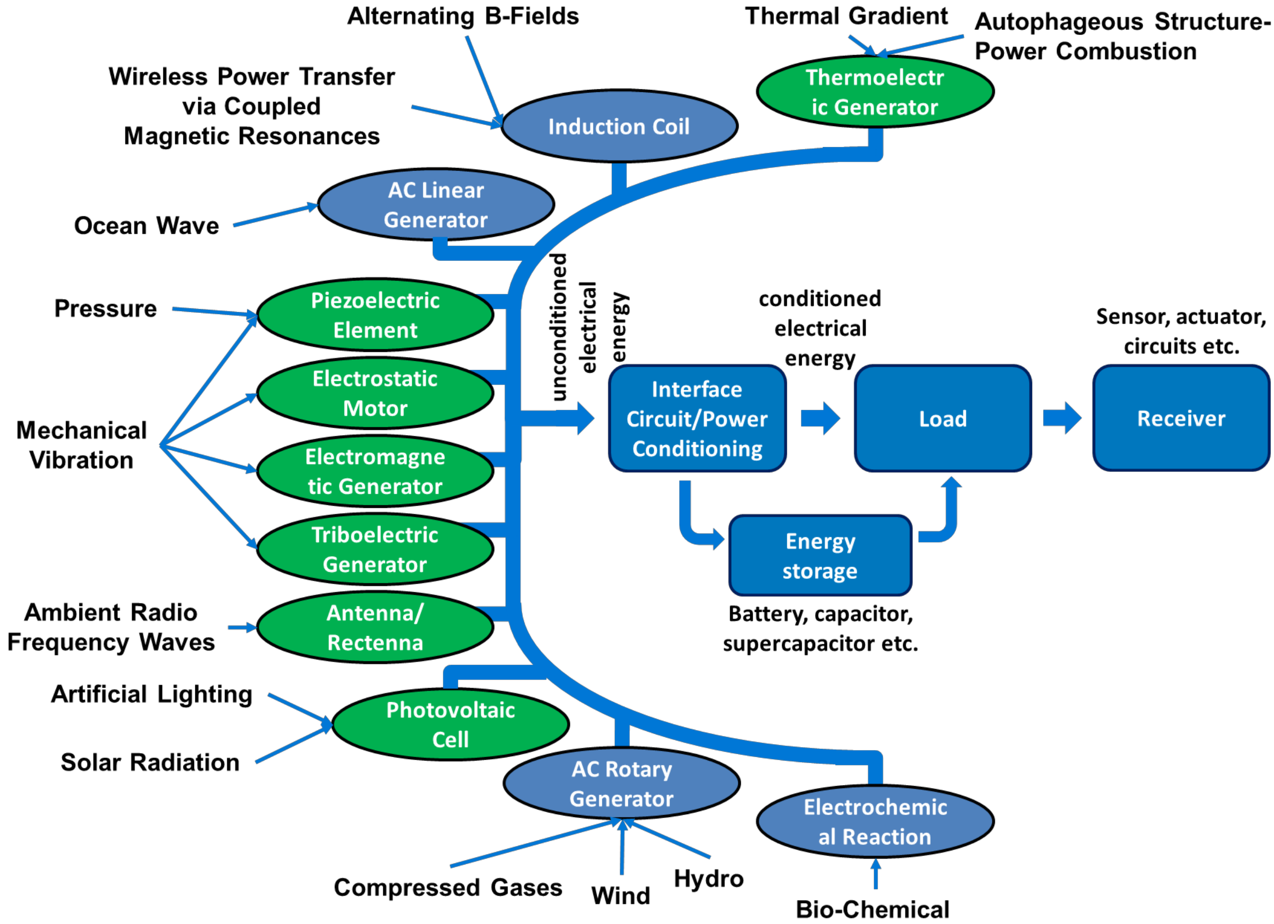

Figure 6: Ambient energy source and corresponding harvesting technologies (Adapted from [24]). Technologies in green are in scope of this report.

These sources then are

- Energy from light
- Thermal energy
- Energy from radio frequency range of the electromagnetic spectrum or induction
- Kinetic energy: motion, vibration, rotation, linear movement

3.5. Harvesting Technologies

An in-depth look on the working principles of existing and emerging EHT is given in Annex C. Table 2 presents an overview of power densities and output voltages of current technologies. The power densities give an estimation of the expected energy the corresponding technologies can deliver at our preferred device size.

3.5.1. Barriers

The drawbacks from current EHT can then be summarized as follows

- The biggest hurdle of implementing EHT is their higher cost compared to conventional batteries.
- Depending on the energy demand of the device the size of the EHT can become bulky.
- Since most EHT generate intermittent power energy storage may be required.

- Current energy storages have shorter life times than EHTs. At the moment a hybrid of Li-Ion-battery and EHT is the optimal combination regarding life times and sustained energy [17].

The development of EHT takes time since it is often fundamental research. There is the danger that industry abandons the technology. For example, small manufactures or startups developing TEG energy harvesters are not primarily selling or developing them with their function as harvesters any more, but as temperature sensor nodes.

3.5.2. Potential

Though the power densities of some technologies are not outstanding and the additional cost may be an obstacle for mass implementation, there are possibilities and good arguments for implementing EHT.

- As the number of IoT devices increases so can also the number of implemented EHT, which may decrease the costs.
- Manufacturer alliances like EnOcean can have lower costs as a purchasing co-op, a larger promotional public appearance and a larger pool of knowledge and resources for product development with EHT.
- The life time of EHT is over 5 years. There are EHT devices which are used already for 15 years without component replacements [25]. Thus, remote devices do not have to be regularly serviced → Life time design without interruptions.
- Extrapolated from past transistor-driven improvements and the inclusion of Cloud-Computing for data processing, it is assumed that the energy consumption of electronics will further decrease, which increases the viability of EHT [16].
- The biggest energy saving potential of EHT is expected in building automation - copper wiring can be reduced, as well as materials, installation, and maintenance costs. See Figure 7, [26] and the report of the EU [26].

Figure 7: Energy-efficiency & Flexibility in Smart Homes and Office Building Automation „Enabled by EnOcean“ [27].

3.6. Related Work

- "Energy Efficiency of the Internet of Things", IEA 4E EDNA Technology and Energy Assessment Report
- "Network Mode Power Measurement", IEA 4E Guidance Note on Measurement and Data Collection
- "Basket of Products Testing", IEA 4E EDNA 4th Meeting Presentation
- "Standby Targets for Networked Devices", IEA 4E EDNA report

3.7. Summary

There is a wide variety of ambient energy sources and corresponding Energy Harvesting Technologies with different states of technical maturity available. The level of deliverable energy from each technology varies also strongly from the low micro-Watt regime to triple digits in the milli-Watt range for device sizes relevant to this work. Yet, this variety is an opportunity to find the suitable Energy Harvesting Technology for IoT-devices and the use-cases which they cover. Some Energy Harvesting Technologies already offer the necessary power output to drive IoT devices. However, implementation is not straightforward. The energy harvester must conform to the use case and the corresponding available ambient energy, subjects which must be considered when starting to design a device. In the next section an overview of different applications in IoT and of some devices which use EHT is given.

4. Applications in IoT

There are many application areas for IoT edge devices powered by EHT. The next section provides some examples of existing IoT edge devices (see Table 4 for an overview) which regulate their power supply with EHT, in the following areas:

- Smart Building
- Smart Infrastructure
- Smart Health
- Smart Environment
- Smart Wearables

Table 4: Overview of EHT used in IoT applications.

Product / Company	Energy Source	EH Technology	Country of origin
Thermostat / en:key	Thermal	TEG	Germany
Wireless Magnet Contact / EnOcean	Light/Solar Energy	Photovoltaic	Germany / USA
Wireless Light Switch / EnOcean	Kinetic energy (pressure)	Electrodynamic/Piezoelectric	Germany / USA
Key Card Switch / EnOcean	Kinetic energy (pressure)	Electrodynamic/Piezoelectric	Germany / USA
Occupancy Sensor / EnOcean	Indoor light	Photovoltaic	Germany / USA
Room Thermostat / Peha - Honeywell	Indoor light	Photovoltaic	Germany / USA
Remote Control / Arveni	Kinetic energy (pressure)	Piezoelectricity	France
Smart Charging at Home / Energous Corp.	RF energy	RF to DC	USA
Fleet Tracking / Perpetuum	Kinetic energy (Vibration)	Piezoelectricity	England
Roads / Sidewalks / Pavegen	Kinetic energy (Vibration)	Piezoelectricity/Induction	USA
Street Lights / EnGoPlanet	Kinetic energy (pressure)	Solar → Day Piezo → Night	USA
Outdoor Temperature Sensor / EnOcean	Light/Solar Energy	Photovoltaic	Germany
Pipeline/Industry Monitoring / Perpetua	Thermal energy	TEG	USA
Sewer Level Monitoring System / NTT Data	Thermal energy	TEG	Japan
Smart Watch / Matrix Ind.	Thermal Energy	TEG	USA

Product / Company	Energy Source	EH Technology	Country of origin
Smart Gardening / EDYN	Light/Solar Energy	Photovoltaic	USA

4.1. Smart Building Applications

EnOcean Alliance is the biggest alliance in this area.

4.1.1.Thermostat

The **en:key** valve controller is screwed on to the radiator valve like a conventional thermostat valve head. As on other radiator thermostats, users can set the desired comfort temperature for the room. The thermostat insert on the valve controller controls the room temperature by opening or closing the heating valve. The valve controller is supplied with power by the integrated thermoelectric generator that uses the thermal energy of the heating water to generate electrical energy. A high-quality internal energy storage unit stores the energy and provides the valve controller with power as required [28].

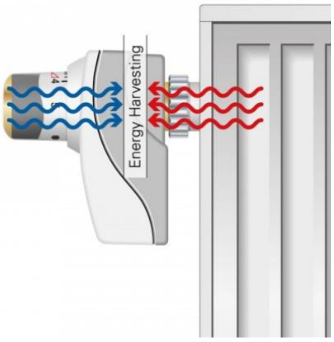

Figure 8:Wireless valve controller without battery [28].

4.1.2.Wireless Magnet Contact

The STM 250 is a solar powered maintenance free magnet contact radio module. An integrated energy store allows unrestricted functionality for several days in total darkness. Using the integrated Reed contact the module monitors the position of the laterally mounted magnet and informs about changes of the status. In addition, a life signal is sent with an interval of about 15 min [29].

Figure 9: Wireless magnet contact sensor [29].

4.1.3. Wireless Light Switch

Self-powered wireless switch for lightning and shading. Self-powered wireless controls are simple to install. The Single and Double Rocker Pads use EnOcean energy harvesting technology to communicate wirelessly with other wireless devices and provide convenient control of lighting, temperature and miscellaneous electric loads [30].

Figure 10: Self-powered wireless switch for lightning and shading [30].

4.1.4. Key Card Switch

The Key Card Switch is one of the simplest, most economical ways to save energy through occupancy based control of lighting, HVAC and miscellaneous electric loads. To operate the switch, guests simply insert their key card in the slot when they enter the room and then remove it when they leave. The key card switch is wireless and can be installed in minutes without having to drill into the wall or run additional wiring. Embedded mechanical energy harvesting element harvests power from the motion of inserting or removing a hotel key card [31].

Figure 11: Self-powered wireless key card switch [31].

4.1.5. Occupancy Sensor

The ceiling-mounted occupancy sensor saves energy and adds convenience by accurately detecting when an area is occupied or vacant. This device is wireless, powered by indoor light using photovoltaic cells, and uses a passive infrared (PIR) sensor to detect motion. The occupancy sensor transmits RF signals to control lighting, HVAC and outlets more efficiently [32].

Figure 12: Self-powered wireless occupancy sensor [32].

4.1.6.Room Thermostat

Universal room temperature sensor with solar energy storage for combination frame with internal dimensions 55 x 55 mm, with change-over switch for two temperature ranges (day / night) for temperature detection and local set point adjustment for individual room controls with integrated temperature sensor. The room temperature sensor transmits the measured values without battery to the receiver [33].

Figure 13: Self-powered wireless room thermostat [33].

4.1.7.Remote Control

Arveni develops piezo electric energy harvesting devices for a wide range of applications, from vibration to pulse harvesting. The device (pictured) uses a piezoelectric energy harvester that converts mechanical energy to electricity by pressing the central green button on the remote-control unit, which provides enough power for several button switches on the remote [34].

Figure 14:Self-powered infrared remote control [35]

4.1.8.Smart Charging at Home

Energous Corporation is the developer of WattUp®—an award-winning, wire-free charging technology that will transform the way consumers and industries charge and power electronic devices at home, in the office, in the car and beyond. WattUp is a revolutionary radio frequency (RF) based charging solution that delivers intelligent, scalable power via radio bands, similar to a Wi-Fi router. WattUp differs from older wireless charging systems in that it delivers power at a distance, to multiple devices – thus resulting in a wire-free experience that saves users from having to remember to plug in their devices [36].

Figure 15: Self-powered wireless room thermostat.

4.2. Smart Infrastructure Applications [36]

4.2.1.Fleet Tracking

The patented electromagnetic energy harvesters convert mechanical energy produced by vibration to electrical energy, which in turn powers the Wireless Sensor Nodes. These nodes transmit real time data back to the desktop or mobile device of the asset owner. The energy harvester is designed to last over 100 years without maintenance, and the sensor nodes 20 years, easily outlasting other battery-only powered systems. This proven, fail-safe technology is also quick and easy to install. The vibration energy harvesters and wireless sensor nodes can be used to monitor valuable equipment and assets across a wide variety of industries, but most commonly used in rail [37].

Figure 16: Vibration energy from train is used to control and connect the train fleet with interne [37].

4.2.2.Roads / Sidewalks

Pavegen uses what it calls a hybrid black box technology to convert the energy of a footstep into electricity, which is either stored in a battery or fed directly to devices. A typical tile is made of recycled polymer, with the top surface made from recycled truck tires. A foot stomp that depresses a single tile by five millimetres produces between one and seven watts. These tiles generate electricity with a hybrid solution of mechanisms that include the piezoelectric effect (an electric charge produced when pressure is exerted on crystals such as quartz) and induction, which uses copper coils and magnets.

Figure 17: Left: people powered football pitch; right: Paris marathon energy harvesting path [38]

4.2.3. Street Lights

EnGoPLANET Smart Solar/Kinetic Street Lights are ideal to be installed at pedestrian zones where people can be directly involved in producing clean and free energy. Every footstep creates from 4 to 8 watts [39].

Figure 18:Self-powered smart street lights from solar energy (left), resp. solar and vibration energy (right) [39]

4.3. Smart Environment Monitoring Applications

4.3.1. Outdoor Temperature Sensor

Battery and wireless outdoor sensor for temperature. Transmission to receiver by means of radio telegrams according to EnOcean standard. With integrated temperature sensor and solar energy storage for maintenance free operation [40].

Figure 19:Self-powered outdoor temperature sensor [40]

4.3.2. Pipeline/Industry Monitoring

Challenge: Measuring temperature, pressure, and flow data are critical to optimize yield quality and production output in steam injection wells for this top tier oil producer. Their preference is to use wireless versus wired sensors, but because of battery life constraints, they have historically been forced to lengthen sensor update rates when using wireless and forego gathering data at the desired update rates. **Solution:** Using Perpetua

Power Pucks for these wireless sensors, the update rates can be configured as fast as 1 second without having to trade-off battery life. This enables the use of wireless versus wired sensors with the ability to configure sensors at rates to meet business requirements [41].

Figure 20:Self-powered outdoor temperature sensor [41]

4.3.3.Sewer Level Monitoring System

These modules were attached to the bottoms of the manhole covers, to monitor the sewer water level 24/7. It is combined with a battery pack and due to the implemented TEG's the battery life time is extended up to 5 years.

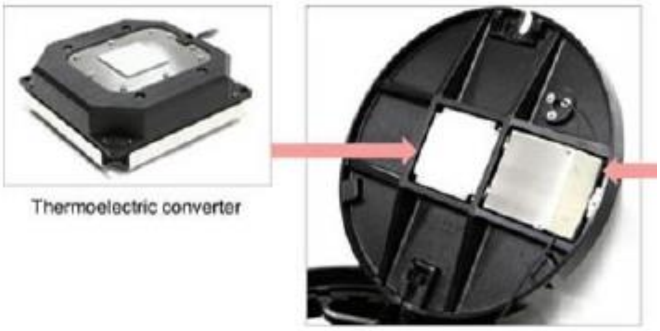

Figure 21: TEG powered sewer level monitoring system [42]

4.4. Smart Wearables

4.4.1.Smart Watch

The MATRIX PowerWatch is the world's first smartwatch that you never have to charge. Powered by your body heat, it measures calories burned, activity level, and sleep using our advanced thermoelectric technology. It is the only smartwatch to feature a power meter which displays how much electrical power you are generating [43].

Figure 22: Self-powered smart watch [43]

4.5. Smart Gardening

4.5.1.Smart Gardening

EDYN Smart Garden System uses solar power to monitor the garden soil with its sensors. The Edyn Garden Sensor tracks light, humidity, temperature, soil nutrition, and moisture — and then cross-references this information with plant databases, soil science, and the weather to give you customized gardening guidance. The Edyn Water Valve tailors watering to fit the plants' needs. It automatically controls existing irrigation system based on data from the Garden Sensor and local weather forecasts to save water, lower utility bills, and never worry about thirsty plants again [44].

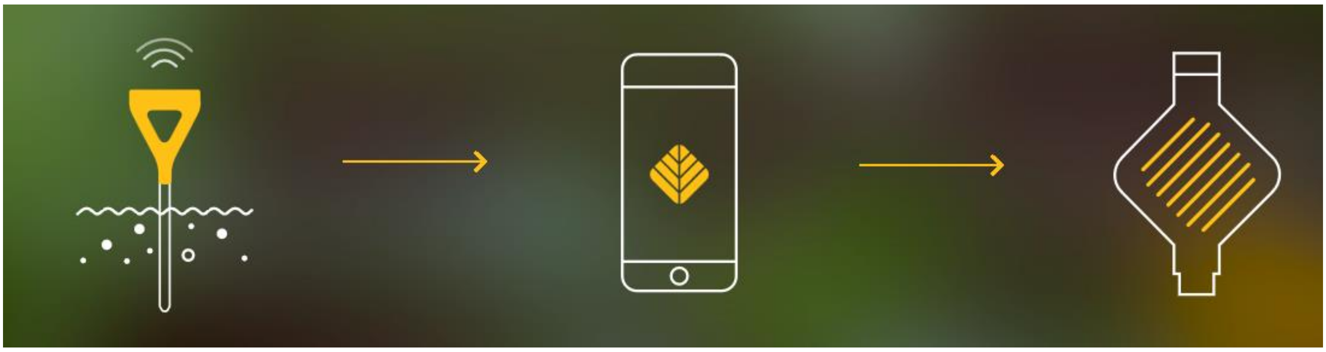

Figure 23:EDYN Smart Garden System. The solar powered sensor pole on the left and the solar powered water valve on the right [44].

5. Device Communication and Load, Power Smoothing and Energy Storage

5.1. Communication Protocols

One of the basic tasks of an IoT device is connection to a network. Different wireless communication protocols can be implemented in the devices to fulfil this task. There are multiple communication protocols with their own advantages and disadvantages. Table 5 presents the commonly used protocols in IoT devices and their properties.

Table 5: Common wireless communication protocols used in IoT devices [45].

Protocol	Properties
Wi-Fi	• High power (>500 mW) • High data rate (>100 Mbit/s) • Low distance (10 m indoors)
Bluetooth Low Energy	• Low power (10 mW) • High data rate (1 Mbit/s) • Low distance (10 m indoors)
Zigbee	• Low power (50 mW) • Medium data rate (250 kbit/s) • Medium distance (25 m indoors)
enocean	• Low power (50 mW) • Medium data rate (125 kbit/s) • Medium distance (50 m indoors)
LoRa	• Medium power (100 mW) • Low data rate (1 kbit/s) • High distance (500 m indoors)

Bluetooth Low Energy (BLE) is a special case: The protocol, like Wi-Fi, is available to most users in their smartphone or tablet and is in constant development to decrease its energy consumption. The first point is an argument why IoT devices prefer BLE and for the second point life time of a coin cell powering a BLE-module is presented in Table 6.

Table 6: Specs and energy consumption of BLE [46].

Comm interval	500 ms	1000 ms
Comm power (mWh) (Tx 1B / Rx 1B)	0.00000794	0.00000863
Power / battery (CR2032)	696 mWh	
Life (days)	507	933
Life (years)	1.4	2.6

These values, however, can be expected for an optimally designed system. One of the tested products containing Bluetooth and a simple sensor node had a specified battery lifespan of up to 6 months which was then reduced to up to 3 months. The EDNA task looked on the standby energy consumption of network interfaces and determined for some communications protocols the achievable low power consumption (see Table 7).

Table 7: Range of power requirements for network standby function based on network interface use [47].

Interface	Total Network Component Power (W)	
	Low	High
Fast Ethernet port	0.3	1.0
Gigabit Ethernet Port, EEE disabled	0.3	0.8
Gigabit Ethernet Port, EEE enabled	0.05	0.5
IEEE 802.11n radio Wi-Fi	0.01	1.1
IEEE 802.15.4 Zigbee	0.01	0.2
IEEE 802.15.4 Bluetooth LE	0.01	0.1
IEEE 802.15.1 Bluetooth	0.01	0.5

5.2. Duty Cycle

An IoT device can generally be in one of the following states

- Off
- On (sensing/processing)
- Standby/sleep
- Communication mode (Transmission/Reception)
- Actuator action mode

This is illustrated exemplary in Figure 24. Figure 25 presents in more detail the communication mode of real device using BLE. The highest voltage spike occur from the wake-up and during reception and transmission.

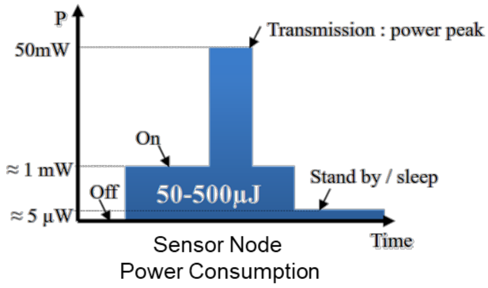

Figure 24: Sensor node power consumption and state diagram from [48].

So, to minimize energy consumption for a specific use case the following parameters (if applicable) can be adjusted

- Appropriate low energy communication protocol
- Maximize periods between RX/TX cycles (High latency between communication periods) – ETSI has set the lower limit to 1 ms for 1 s operating time for short range devices. Transmission duty cycles for devices (BLE, IEEE 802.15.4, LoRa) are e.g. limited up to 1% of the operating time (i.e. max. of 36 s in 1 hour) in Europe [49] [50]
- Reduce sample rate of sensor measurement to practical values (No need to measure a temperature every half a second)
- Outsource data processing to the cloud
- Reduce data throughput
- Low latency (no added extra processing to signal) during transmission

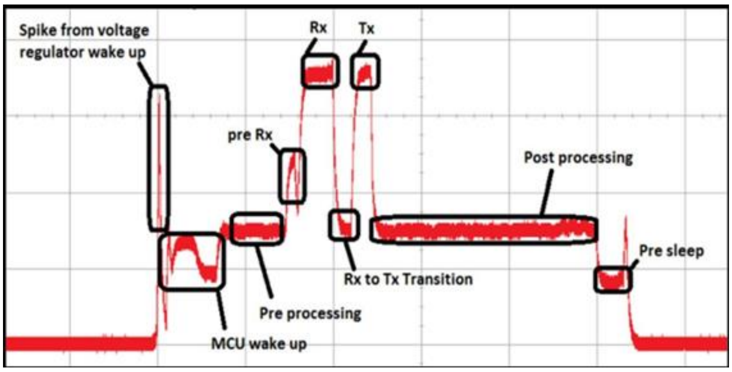

Figure 25: BLE time-resolved connection event. Image taken from [46].

The device load is intermittent as is also the harvested energy (see Figure 26). These two including their amplitudes do not usually overlap, thus, an energy storage solution is needed for the following points:

- Smoothing of power
- Supply of additional energy to compensate deficient energy from the harvester
- Storage of excess power from the EHT for later use

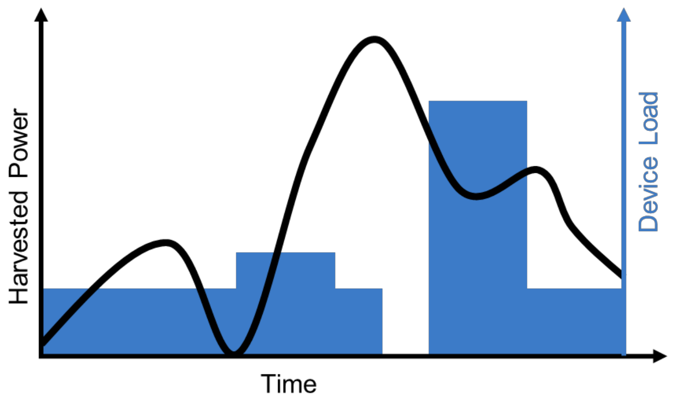

Figure 26: Time development of device load and harvested power.

Since most IoT-devices are sensor nodes, the power demand of the sensor type must also be kept in mind for the load. Table 8 presents typical power demand of some generally used sensors.

Table 8: Overview of different sensor types and their power demand. From [18].

Analog Sensors	Power
Pressure	1 – 20 mW
Acceleration	3 – 35 mW
Temperature	378 – 600 µW
Humidity	1 -3 mW
Gas	< 800 mW
Displacement	< 1 mW
Digital Sensors	**Power**
Humidity / Temperature	3 mW
Pressure, Temperature	6.5 mW

An IoT sensor node should, thus, consume power from the high micro-Watt regime to the single-digit milli-Watt range.

5.3. Standards for EHT

Interoperability of different end products is an important success factor in establishing sensor solutions on the market with energy harvesting technologies. As there are different players in the supply chain, with different approaches towards the integration of EHT into final products and applications, interoperability might be compromised, see Figure 27. In this context, there are three important standards policy makers should know about.

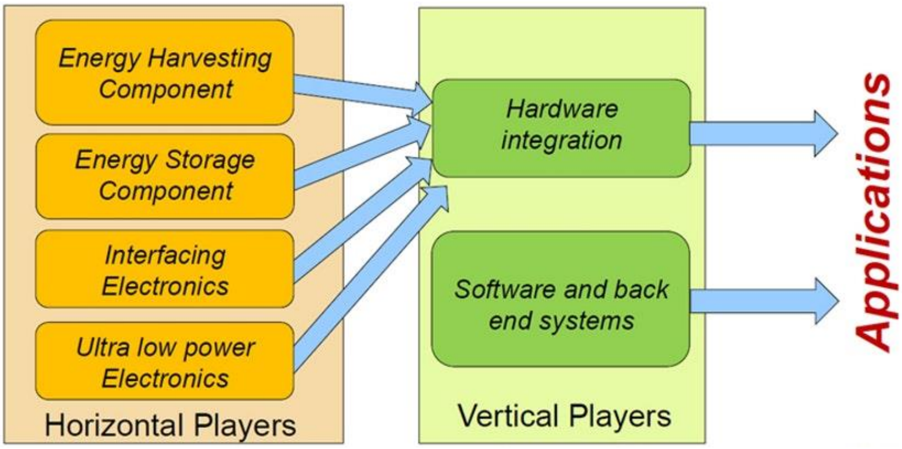

Figure 27: Supply chain for energy harvesting [51].

The EnOcean Alliance pursues the standardization of communication profiles (EnOcean Equipment Profiles), ensuring that the entire product portfolio of self-powered wireless switches, sensors and controls can communicate with each other[4]. The EnOcean wireless standard is geared to wireless sensors and wireless sensor networks with ultra-low power consumption. It also includes sensor networks that utilize energy harvesting technology.

In 2012 the EnOcean wireless standard became the standard ISO/IEC 14543-3-10:2012 Information technology -- Home electronic systems (HES) architecture -- Part 3-10: Wireless short-packet (WSP) protocol optimized for energy harvesting -- Architecture and lower layer protocols. This protocol is efficient enough to support energy harvested products for sensors and switches that do not require wires and batteries. It is the only standard specifically designed to keep the energy consumption of such sensors and switches extremely low. It achieves this by transmitting multiple, very short transmissions; and by selecting radio frequency bands with excellent signal propagation and minimal interference. The standard utilizes the less crowded 868 MHz and 315 MHz frequency bands, making it suitable for use worldwide (Interoperable products from various manufacturers are available at 868 MHz for Europe and China, 902 MHz for North America and 928 MHz for Japan). This provides a safeguard against other wireless transmitters, offers fast system response and elimination of data collisions, and has good penetration through materials like walls and furniture. This makes the 868 MHz and 315 MHz band suitable for reliable building automation [52].

[4] The EnOcean Alliance is a consortium of over 60 companies working to further develop and promote self-powered wireless monitoring and control systems for sustainable buildings by formalizing the interoperable wireless standard: www.enocean-alliance.org

Figure 28: Interoperable wireless standard for home and building automation [53].

The ZigBee Alliance also created an extension to the existing ZigBee PRO standard, to use a greater selection of available energy harvesting solutions. It is called the ZigBee PRO Green Power feature. ZigBee Green Power is used in conjunction with a ZigBee application profile (e.g., Home Automation) for the ZigBee PRO wireless network protocol. ZigBee Green Power minimizes the power demands on a node that participates in a ZigBee PRO network by:

- Employing shorter data frames (simple IEEE 802.15.4 frames) that take less time to transmit, thus reducing the amount of energy needed for each transmission.
- Not requiring these nodes to be full, permanent members of the network and allowing them to only transmit data when they need to (e.g., when a button on the node is pressed).

A Green Power frame is sent to a 'proxy' node, which is a normal network node and which embeds or 'tunnels' the Green Power frame within a normal ZigBee frame for re-transmission through the network. The Green Power cluster is not needed on the source node but must be used on the proxy nodes, as well as the 'sink' nodes that need to receive and interpret the tunnelled Green Power frames [54]. The basic Green Power mechanism for sending a frame of data is illustrated in Figure 29 below.

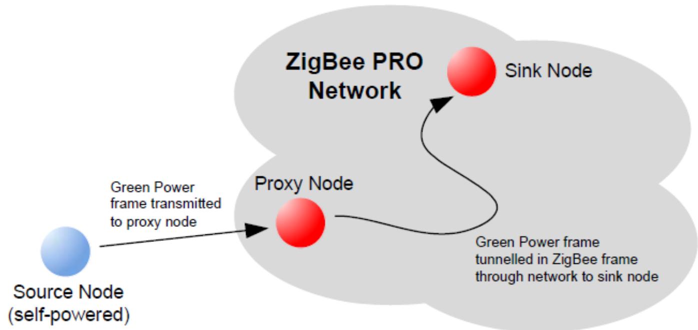

Figure 29: Basic ZigBee Green Power mechanism [54].

As mentioned before, Bluetooth Low Energy (BLE) is also available and widely used for low-power wireless communication in applications requiring the transfer of data within a relatively small radius, typically less than 10 meters (For a wireless sensor node, data can be collected and sent to e.g., a smartphone). Figure 30 shows a typical application flow for these types of sensor nodes [55]. BLE is also being considered for energy harvesting. BLE is designed for very low power operation, and is optimized for data transfer solutions (when enough energy has been saved, a sensor can perform tasks such as collecting data and transmitting it over BLE to another device). To enable reliable operation in the 2.4 GHz frequency band, it leverages a robust Adaptive Frequency Hopping approach that transmits data over 40 channels [56].

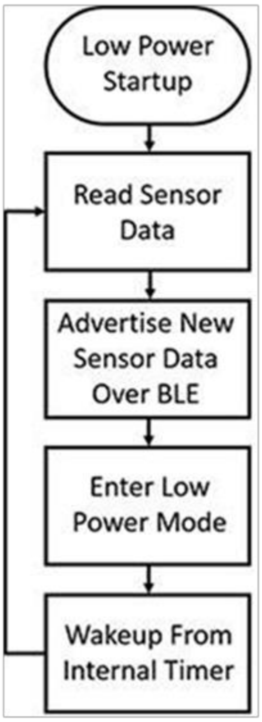

Figure 30: Typical flow diagram of BLE sensor devices [57].

With these standardized options product developers have flexibility for product designs, considering the options needed for data rates, power levels, security and network topologies, and as such EHT could be implemented more broadly in a variety of applications.

5.4. Energy Storage

Since the goal is to reduce battery waste the energy storage must have a longer life time than a battery. Supercapacitors can fulfil this role. Supercapacitor is an enhancement of classical capacitors. A Supercapacitor contains added electrolytes and a separator membrane compared to classical capacitors (Figure 31). This increases the charge capacity 6-12 orders of magnitude compared to a classical capacitor. However, Supercapacitors cannot store energy for as long as a battery. They will self-discharge over a period of some days. A supercapacitor with a capacity of 600 F will still retain 50% of its initial voltage after around 150 hours [58].

Traditional Capacitor **Have a dielectric between the electrodes**		**Supercapacitor** **Have an electric double layer between electrolyte and each electrode (two capacitors in series)**
No electrolyte	Electrolyte to contact/heal thin dielectric on porous electrode	Has electrolyte to create double layer No dielectric

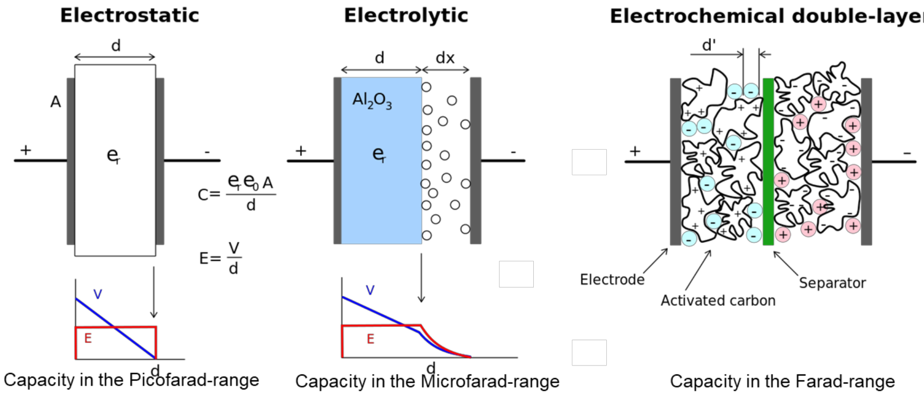

Figure 31: Schematic of a Capacitors and Supercapacitors [58] [59].

Table 9: Electrolyte Impact on Performance Increase in Supercapacitors [60].

	Organic Electrolyte (TEABF4)	Aqueous Electrolyte (H2SO4, KOH)	Aprotic Ionic Liquids (AILs)
Operating Voltage	2.7-2.8 V	0.7-0.8 V	3.0-3.5 V
Conductivity	~ 0.02 S/cm	~ 1 S/cm	~ 0.005 S/cm
Maximum Capacitance	150-200 F/g	250-300 F/g	100-120 F/g
Technological, economical and safety aspects	• Require manipulation in inert atmosphere • Expensive • Environmentally unfriendly	• Easy manipulation • Not expensive • Environmentally friendly	• Performing at high temperature (40-60°C) but decreasing stability • Expensive • Environmentally friendly

A battery can perform before its nominal capacity falls below 80% of its initial rated capacity 500-1200 charge and discharge cycles. Supercapacitors have 500,000 – 1,000,000. Supercapacitors are 5-10x more expensive for the $/kWh. However, their life cycle is around 500 to 1000 times higher. The supercapacitor comes then out ahead when comparing energy or power cost per cycle

- 0.01 $/kWh/cycle compared to 0.375 $/kWh/cycle of the Lithium Ion battery [58]
- 0.005 $/kW/cycle compared to 0.13 $/kWh/cycle of the Lithium Ion battery [58]

6. Evaluation of IoT devices

As shown in chapter 4, there are lots of different IoT-devices and use cases. For this chapter several battery-powered devices were selected according to the relevant IoT application areas. These operate in an environment with potential for implementing EHT and use a variety of communication protocols. The energy consumption of these devices (in normal use and standby, if applicable) will be determined to estimate the conditions for this implementation.

6.1. Selected Devices

6.1.1. Smart Home Devices

From "Smart Home" system family the following two devices were selected:

- Smart thermostat for radiator
- Door/Window contact sensor

Figure 32: Smart Home system [61].

The system uses an access point as a gateway to connect to a Cloud-Service and to connect with the tablet or smartphone of the user. In Europe the devices are using an communication protocol on the 868 MHz frequency band developed by the manufacturer which has been open sourced.

6.1.2. Advanced Connected Fire detector

The third product (Figure 33) is a fire detector with multiple sensors (smoke sensor, CO sensor, heat sensor, humidity sensor, presence detection, ambient light sensor and a microphone) and multiple communication protocols (Wi-Fi 802.11b/g/n protocol, Wireless Interconnect (IEEE 802.15.4), Bluetooth Low Energy (BLE)) and using "Wireless Interconnect" multiple detectors can communicate by forming a mesh.

Figure 33: Fire Detector [62].

6.1.3. Sensor Nodes with Bluetooth

The selected sensor nodes are battery powered sensor nodes using Bluetooth Smart (BLE) to communicate with the smartphone of the user. Two smart sensor types were evaluated:

- Smart wireless thermometer
- Smart anti-theft alarm (Motion detector)

Figure 34: Sensor nodes for temperature sensing and motion tracking [63].

6.1.4. Tracking Device with Bluetooth

The sixth device is a tracking device which can be attached to a keychain or backpack or any other personal belonging. The Chipolo also uses Bluetooth Smart (BLE) to communicate with the smartphone of the user. You can let your Chipolo ring using your smartphone to locate your belongings or use the Chipolo to let your smartphone ring for locating your phone.

Figure 35: Tracking device with Bluetooth [64].

6.1.5. Smart Plant Pot

The last device is a smart plant pot with multiple sensors (Ambient light sensor, temperature sensor, soil humidity sensor and fertilizer sensor), a water pump and Bluetooth Smart (BLE) for communicating with the user's tablet or smartphone.

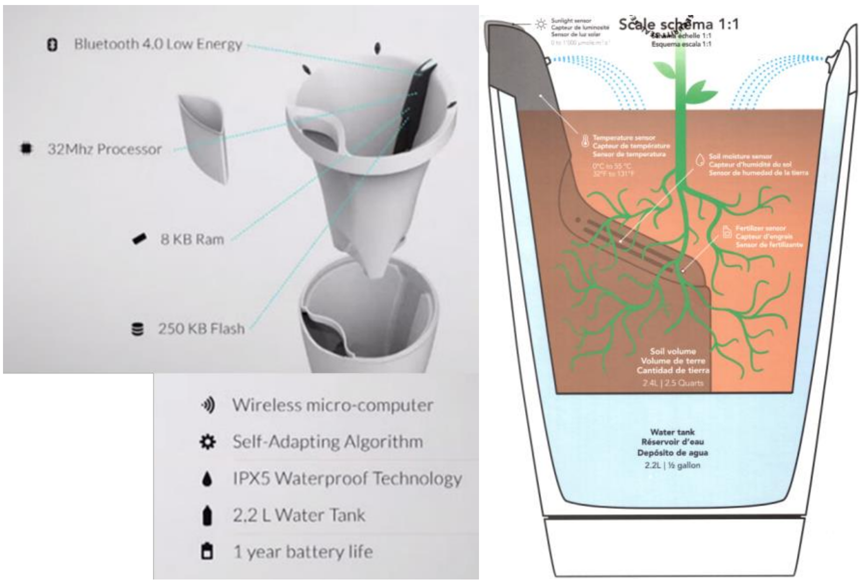

Figure 36: Smart plant pot Parrot Pot [65].

6.2. Measurement of Power Consumption

6.2.1. Test Setup

For determining the energy consumption of the selected devices, the following test setup was used:

- A laboratory DC power supply as substitute for the device batteries
- A Teledyne Lecroy Oscilloscope and clamp-on ampmeter for general overview of the range and the behaviour in time of the current and supply voltage
- Keysight Electrometer for the measurements of very weak currents in the pA range
- Laboratory-grade Yokogawa and Xitron power meters

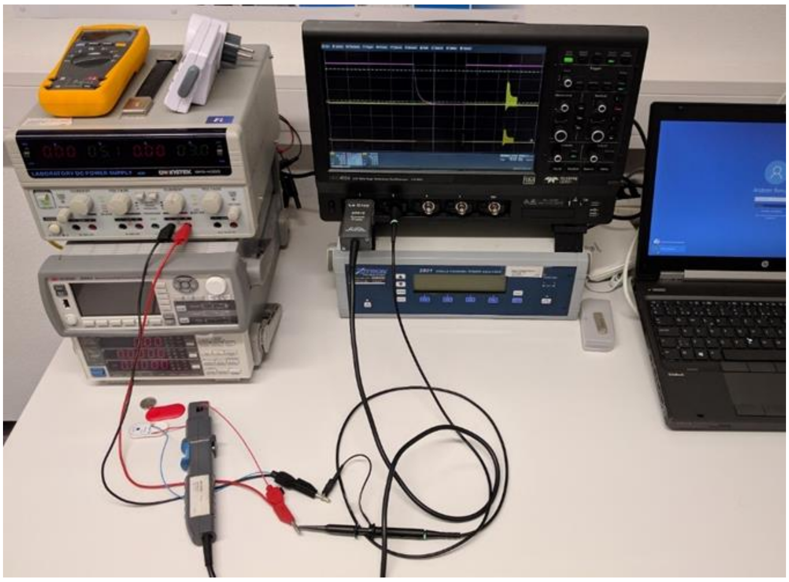

Figure 37: Laboratory test setup for measuring the energy consumption of the IoT devices (Photo: Helbling Technik AG).

6.2.2. Measurement Procedure

For the measurement process EDNA "Network Mode Power Measurement Guidance Note on Measurement and Data Collection" from 21st Sept. 2015 was taken as a guideline and adapted as appropriate. The procedure is presented in Figure 38. The device is always monitored with a Power Meter, current clamp and a voltmeter during Pairing Mode, Network Mode 1 and Network Mode 2. In both network modes the devices are observed for over an hour to observe possible standby modes.

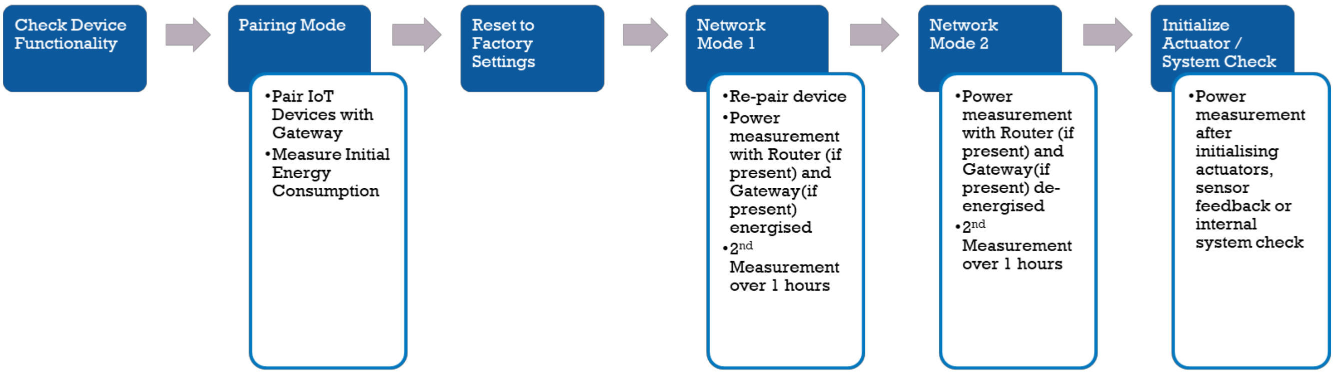

Figure 38: Measurement Procedure.

6.2.3. Results

Table 10 presents the results of the measurement. Generally,

- The highest power consumption takes place when either actuators, pumps or buzzers are activated
- The lowest power consumption (baseline) takes place between communication of the IoT device with the gateway or the mesh
  - It varies between 1 mW to 20 mW per device

  - Tx/Rx duty cycle, the time between communications denoted in brackets, varies also between devices
- Peaks that takes place during communication are around 70 mW to 150 mW. This is around the expected values for the communication protocol

6.3. EHT Concepts

In the following subsections two exemplary use cases with EHT for some of the selected IoT devices will be presented. However, integrating EHT in a finished product is not plug & play. Design guidelines say that best practice is that the energy harvester must conform to the use case and the corresponding available ambient energy. Subjects which should already be considered when starting to design a device.

This involves a rethinking of the device design process adding additional initial development costs. Nowadays, the amount of available IoT devices is already becoming staggering, but the number of devices using EHT is also getting large. This increase in public perception makes EHT more well-known by users and manufacturers. The larger presence and industry alliances which promote EH can alleviate this initial development costs due to use of best practice design guidelines or common promotion.

6.3.1. Use Cases – Scenario A Wireless Sensor Node – Smart Displacement Sensor

A sensor node with low power sensor (acceleration/displacement) and alarm speaker to be used as a mobile "Smart Anti-Theft Alarm".

The sensor itself is a low power consumer (< 1 mW). In our tested devices communication module and buzzer have a power demand of 70 mW and 1 W respectively (see the sections on load and communication protocols). The processing and communication system will use next to the buzzer most of the power and should be optimized. In an optimized case with around 10 to 20 mW.

As mobile "Smart Anti-Theft Alarm" (in e.g. backpack) it would be suited for vibrational Energy Harvesting with energy storage. A Person walking 60 seconds with a speed of 4 km/h would generate a power of 2.15 mW with magnetically plucked wearable knee-joint energy harvester. Prototype electrodynamic vibrational Energy Harvesting at a brisk pace could generate power of around 64.8 mW

This is sufficient to drive the sensor. Communication should only take place with the smartphone (since the sensor is mobile) when guarding mode is activated and when the sensor is moved. The buzzer itself should only activate if sufficient energy is in storage otherwise only smartphone speaker should raise alarm

6.3.2. Use Cases – Scenario B Complex IoT Device – Smart Plant Pot

The Smart Plant Pot user low power sensors for humidity, soil fertilizer, light, temperature and water tank level. Their power demand is less 20 mW. The communication module and pump for watering are the largest energy consumers with 1.1 W and 2.3 W respectively.

Given the environment needed for plants a photovoltaic Energy Harvester is suited best for this use case. All sensors are low energy consumers and can be powered without energy storage by the photovoltaic Energy Harvester during day time.

However, (multiple) supercapacitors as energy storage would be required to drive the pump and communicator during initialization and Network Mode 1. User convenience and no semi-annual changing of 4 AA batteries could outweigh the higher cost for supercapacitors.

Table 10: Measurement Results

Product	User Interface	User Link	Gateway	Product Link	Battery Type & spec. Replacment Cycle	Peak Power Consumption in W					Average Power Consumption in W	Comments
						Inital Pairing	Network Mode 1	Network Mode 2	Inititalize Actators, Sensors	Baseline Power Consumption between Rx/Tx Action		
Smart Home Door/Window Contact	Smartphone App	Wi-Fi 802.11b/g/n	Access Point	868 MHz Band	1x AAA (alkaline) not specified	0.15	0.1	0.1	0.17	0.003 (500 ms)	0.15	Energy Consumption Gateway 1.2 W
Smart Home Thermostat	Smartphone App	Wi-Fi 802.11b/g/n	Access Point	868 MHz Band	2x AA (alkaline) not specified	0.46	0.06-0.1	0.06-0.1	0.25 - 0.4	0.003 (500 ms)	0.15	Energy Consumption Gateway 1.2 W
Fire Detector	Smartphone App	Wi-Fi 802.11b/g/n	Router	-Wi-Fi 802.11b/g/n -Wireless Interconnect (IEEE 802.15.4) -Bluetooth Low Energy (BLE)	6x AA (lithium) 5 years	1.8	0.12	0.12	1.8	0.02 (10 s)	0.61	Buzzer Monthly test routine
Fire Detector (Mesh)	Smartphone App	Wi-Fi 802.11b/g/n	Router	-Wi-Fi 802.11b/g/n -Wireless Interconnect (IEEE 802.15.4) -Bluetooth Low Energy (BLE)	6x AA (lithium) 5 years	1.8	0.12	not applicable	1.8	0.02 (10 s)	0.61	Speaker Monthly test routine
Sensor Node Thermometer	Smartphone App	Bluetooth Low Energy (BLE)	Smartphone/ Tablet	Bluetooth Low Energy (BLE)	1x CR2025 up to 3 months	1.1 (speaker)	0.08	0.08	not applicable	0.001 (2500 ms)	0.1	Has buzzer
Sensor Node Motion Sensor	Smartphone App	Bluetooth Low Energy (BLE)	Smartphone/ Tablet	Bluetooth Low Energy (BLE)	1x CR2025 up to 3 months	1 (speaker)	0.07	0.07	0.7	0.001 (2500 ms)	0.1	Has buzzer
Tracking Device	Smartphone App	Bluetooth Low Energy (BLE)	Smartphone/ Tablet	Bluetooth Low Energy (BLE)	1x CR2025 1/2 year	0.17	0.12	0.12	0.17	0.001-0.003 (2500 ms)	0.003	Has buzzer
Smart Plant Pot	Smartphone App	Bluetooth Low Energy (BLE)	Smartphone/ Tablet	Bluetooth Low Energy (BLE)	4x AA (alkaline) 1 year	1.1	1.1	0.15	2.3	0.02 (-)	0.18	Has water pump

6.4. Summary

As demonstrated in EHT Concepts and in chapter 3, some Energy Harvesting Technologies already offer the necessary power output to drive IoT devices. However the complexity of the use case and of the device may result in the device not being able to use the apparent EHT. It can be more worthwhile to separate the complexity of the use case to multiple devices. The use of multiple EHTs in one device to cover the different environments with their ambient energy is also a possibility.

The total component costs for EHT itself (energy harvesting transducer, power conditioner, energy storage) will in the foreseeable future not get lower than the cost for a battery. The quantity of produced batteries compared to EHT is one factor. This applies even for EHT like the triboelectric nanogenerator, electrodynamic EH, photovoltaic EH, thermoelectric EH and capacitive including electret EH which are suitable for low cost mass production [20].

In many cases, there is a need for energy storage to smooth the generated intermittent energy and to have it available when the device requires. Supercapacitors with their long lifetime compared to batteries is also viable as environmentally-friendly possibility.

7. Recommendation

This section describes five recommendations to policy makers for increasing the potential, and/or for overcoming the barriers for the implementation of EHTs. Those are:

1. **Providing information and training qualification for professionals**
2. **Providing information to end-users**
3. **Exploring synergies with building standards to include EHT**
4. **Using EHT in specific applications and promoting demonstration projects**
5. **Designing and supporting research programs for EHT development and deployment**

In Chapter 3.5 the barriers and opportunities of EHT have been discussed. Barriers are associated with higher costs, design constraints due to intermittent harvesting, energy storage and size, and the long development cycle of the EH solutions. As discussed previously, wireless sensor networks are the most promising area of application for energy harvesting devices, especially for industrial applications, infrastructure, and buildings. This is followed by specific applications of EHT with potential to power consumer and mobile electronics as well as medical devices. This potential relates is a result of long life times and installation without wiring (reducing materials, installation, and maintenance costs).

Recommendation #1:
Providing information and training qualification for professionals

For the selected products investigated in this study, it was possible to identify specific design changes that would allow the use of EHTs, which might show that potential exists to incorporate EHTs in other edge products. To fully leverage the potential of the energy harvesting technology designers should learn a different approach to power management. A lot of focus is traditionally put on increasing the energy source, for example with designing for a bigger battery instead of reducing the consumption of the devices. A different approach would be to design low-power processors which only turn on blocks of processing power when really needed. This same principle of intelligent power management can be applied to the design of IoT devices and wearables, to allow energy harvesting to be a viable solution not just for supplemental power, but to provide battery free power over the device lifetime [66].

Concerning the installation of energy harvesting ecosystems for networks of sensors, for example in buildings, there are critical factors such as range, installation efforts and flexibility, data volume, availability of information, reliability, and costs. System designers need to know the levels of data transmission in a building (e.g., across many floors to a central point, or in a floor, or even in single rooms). This might demand different solutions, which also need to consider, in the case of wireless networks, the possible interference with other active systems (Mobile phones, Bluetooth, etc) in the same frequency band range. This means that professionals need to have the knowledge to evaluate these different factors when planning reliable network systems. Lack of proper installation and commissioning can reduce market confidence in the quality of the technology.

The provision of information and professional training/qualification is an area where policy makers could develop strategies to advance the implementation of EHTs.

Recommendation #2:
Providing information to end-users

EHTs are visible to end consumers at the level of wearable products already in the market, especially for charging mobile phones and other small devices (e.g., in shoes, small thermal generators, bags with flexible solar panels, and more, see photos in Figure 39). This awareness could be strengthened by providing information about the installation of EHT in premises where users are active, and as such they can be informed about the impacts of the locally generated forms of energy, not only at large scale (PV panels or wind turbines), but also for EHT edge devices. This could be part of a smart energy strategy for new and/or retrofitted buildings, with the incorporation of energy management systems, and/or automation with actuators and sensors using EHT.

Energy efficiency policy makers could (for example in cooperation with smart home system providers, energy utilities) promote components incorporating EHT, and provide guidelines for energy efficient smart home installations.

Further policy makers could consider developing methodologies to assess the performance of EHT components, (energy harvesting power range and the power availability under certain conditions), and with this performance, an information and/or endorsement label could be developed.

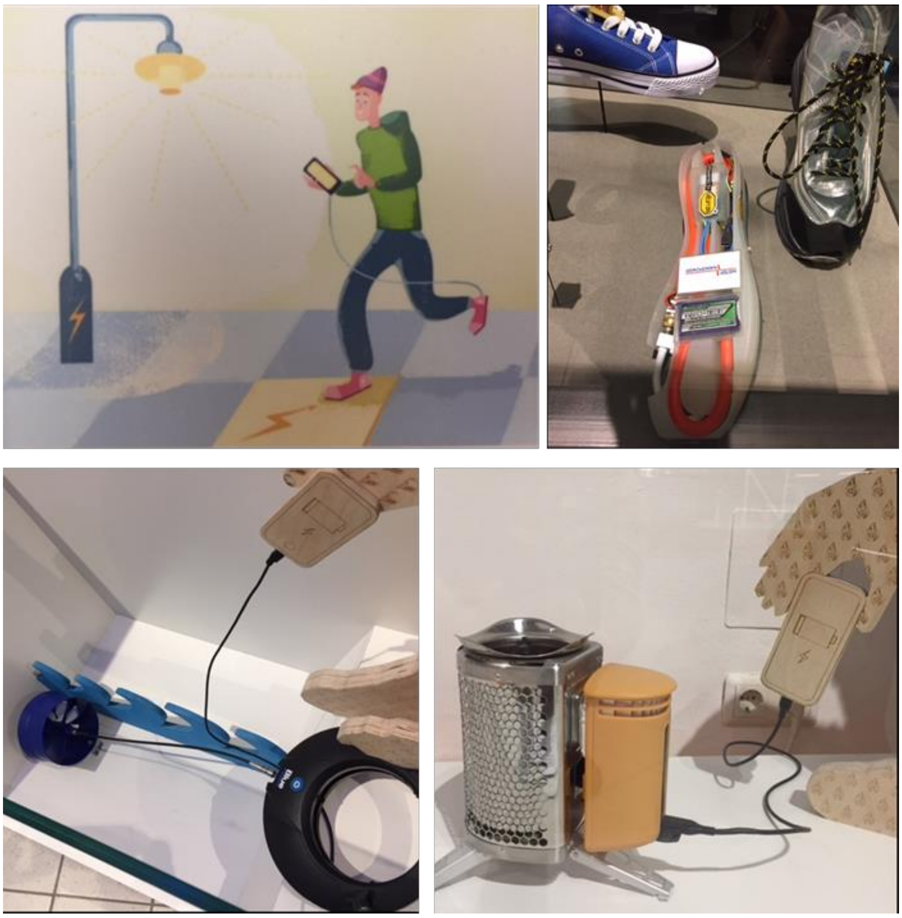

Figure 39: “On-Off Exhibition”, Technical Museum Vienna, January 2018. From L to R: InStepNanoPower from Vibram, portable generator from Blue Freedom, and BioLite camp stove (Photos: A. Díaz).

Recommendation #3:
Exploring synergies with building standards to include EHT

There are regulations, standards and even labelling schemes available in various countries and regions for buildings, e.g., in Europe there is the Energy Performance of Buildings Directive (EPBD) and the voluntary standards/labels Passive House in Germany [67], Minergie in Switzerland [68], and Casaclima in Italy [69]. For example, in the Minergie scheme there is the requirement of installing energy monitoring systems (from certain size of constructed area), and a list of authorized/recommended equipment providers is also available [70].

There are requirements in building standards concerning the main building and end-user loads[5]. In the Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings (ANSI/ASHRAE/USGBC/IES Standard 189.1-2014), under the section (7) Energy efficiency already considers the prescriptive option[6] for the interior lighting power, with the provision of occupancy sensors and lights control. In these examples, synergies could be explored to include an EHT option associated to the energy monitoring and the automation systems.

Policy makers could consider the possibility of including provisions for the use of EHT (e.g., in wireless sensor networks) within the specification of existing building standards and schemes.

Recommendation #4:
Using of EHT in specific applications and promoting demonstration projects

Governments could consider mandating the use of energy harvesting in specific applications, as they have mandated the deployment of smart meters, RFID, and photovoltaics. For example, legislation in the UK requires carbon monoxide sensors in every classroom. In such applications, conventional batteries might not work under all conditions and energy harvesting powered solutions might be advantageous [51].

Policy makers could also consider supporting EHT demonstration projects, to promote the interaction of people with EHTs. A project example is the installation of the company Pavegen, with a 10-square metre area in a shopping district in London, which harvests energy from walking to power lighting and ambient bird sounds, while collecting data on the energy produced. The energy harvesting walkway will also scan Bluetooth-enabled phones, interacting with apps to reward users for their steps on the pavement with discounts, vouchers and education resources. This "Pavegen" is part of an installation showcasing the latest in sustainable technologies, bringing together energy harvesting, data collection and pollution reduction.

[5] Main building loads are those associated with the installed systems such as lighting and heating/ventilation/air conditioning (HVAC). Appliances and other equipment are considered as user loads.
[6] The prescriptive option consists in giving specific technical requirements for a set of envelope and technical system elements or characteristics. The performance option consists of giving limits on energy needs, i.e. for heating and cooling, and/or for total primary energy.

Figure 40: Example Pavegen´s energy harvesting walkway [38].

Recommendation #5:
Designing and supporting research programs for EHT development and deployment

As discussed in this report, the ultimate goal of energy harvesting systems for IoT is to shift the paradigm from battery-operated edge devices to an autonomous energy harvesting that only relies on energy harvested from the ambient environment. Research and development challenges for energy harvesting relate to advancements in various layers of design (e.g., miniaturized generic harvesters which can be used in different environments with dynamic energy sources) and also in integrating the advances from circuits and devices that harvest and transfer energy.

Policy makers could design and support research programs for the development and deployment of EHT with sufficient funding over time to overcome the risks of demonstration investment, generate a track record on performance, and even explore standards for comparison and compatibility.

Specific uses and needs of industrial sectors for monitoring could serve as the start point to launch research programs, to find innovative solutions. For example, the European Union research program Horizon 2020 did launch the “Zero Power Water Monitoring Horizon Prize”. It is challenging innovators to come up with solutions based on self-powered and wireless smart sensing technologies designed for real-time monitoring of water resources. This Horizon Prize will award € 2million to any entity (innovators, small and medium size enterprises, and non-profit organizations acting alone or together with other entities) that will come up with a breakthrough solution able to boost self-powered energy consumption in Smart Water Management System [71].

Annex A Abbreviations and Terms

The common terms and abbreviations used throughout this document are described in Table 11. The following table defines the terms and abbreviations specific for this document.

Table 11: Abbreviations and terms used in this document.

Abbreviation	Meaning
4E	Energy Efficient End-Use Equipment
AG	Aktiengesellschaft - Joint-stock company
AM	Air Mass, the direct optical path length through the Earth's atmosphere
BLE	Bluetooth low energy
Comm	Communication
EDNA	IEA 4E Electronic Devices and Networks Annex
EH	Energy Harvesting
EHT	Energy Harvesting Technology
EMPA	Swiss Federal Laboratories for Materials Science and Technology
IC	Integrated Circuit
IEA	International Energy Agency
IoT	Internet of Things
NEDO	New Energy and Industrial Technology Development Organization
Rx	Receiver
TEG	Thermoelectric Generator
TENG	Thermoelectric Nanogenerator
Tx	Transceiver
PV	Photovoltaic
ZHAW	Zurich University of Applied Sciences

Annex B Research Activities in Energy Saving and Harvesting in some EDNA Member States

a. Switzerland

In Switzerland low power and energy saving projects and studies exploring the potential of EHT funded by the federal government are conducted. Also selected swiss universities and their spin-offs are developing EHTs and validation methods in IoT devices:

- Study and Report about “Energy Efficiency of the Internet of Things”
- Study about the potential of thermoelectric generators (TEG) “Das Potenzial der Thermoelektrik”
- Startup company “Smart Home Technology” is developing an add-on module specifically designed for IoT devices to significantly reduce their standby energy consumption to almost zero
- Startup company greenTEG AG founded as spin-off of the Swiss Federal Institute of Technology (ETH) is developing TEG EHT, however, nowadays the focus more on the application as a sensor node of the TEG
- Swiss research institutes like ZHAW and EMPA participating in the “Waste Heat Recovery/Energy Harvesting” meetings organized by the Swiss Federal Office of Energy
- The Computer Engineering and Networks Laboratory group of the Swiss Federal Institute of Technology (ETH) is developing a method for fast and accurate “Measurement and Validation of Energy Harvesting IoT Devices”

b. Austria

EHT development research is mostly done at Austrian universities and research centers, together with selected companies, e.g., Railways. Applications include sensors for tracking containers in trains (vibration), and data on airplanes (temperature changes). Few market EH products are made in Austria, examples are: the flexible film sensor Pizoflex from Joanneum research, and an energy harvesting wireless sensor IC for EnOcean.

c. Japan

Japan promotes with NEDO EHT with support from industry partners like NTT Data. It already plans to propose standardization, implementation and performance measurement guidelines (see Figure 41).

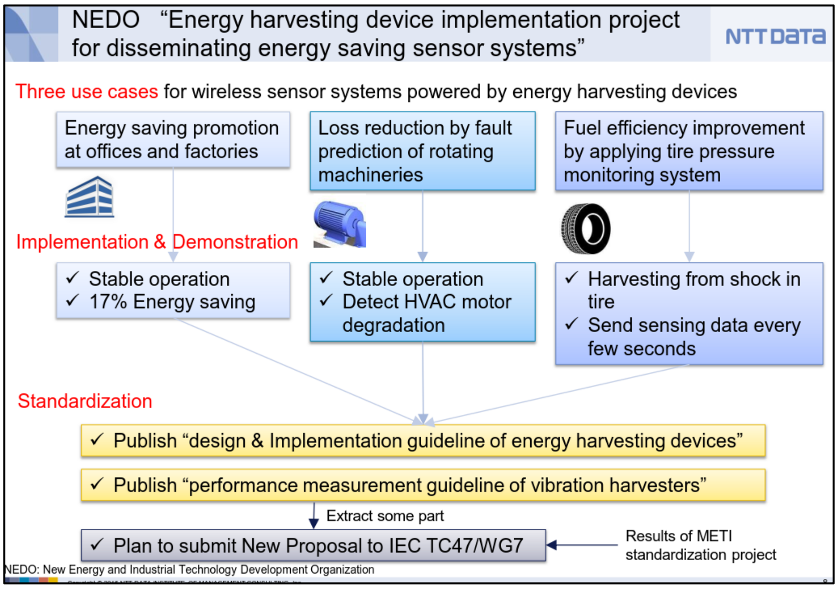

Figure 41:NEDO proposal for EHT development standardization [42]

Additionally, in 2017 a commercially viable showcase project for "Smart Agriculture" called e-Sensing for Agri provided by NTT East is using long-distance wireless sensor systems developed by Nissha Printing Co., Ltd. and Nissha Group company SiMICS Co., Ltd.. This long-distance wireless sensor system requires no external power source since it is using an EnOcean long-distance low power, wide area communications technology with energy harvesting technology. Nissha and SiMICS are members of the EnOcean Alliance.

Annex C Energy Harvesting Technologies

a. *Existing and Emerging EHT*

As discussed in subchapter 3, there are different ambient energy sources available for EHT. This subchapter describes various EHT categorized by the ambient energy source, which is used to produce electrical energy. The four most typical energy sources for harvesting procedures, kinetic (a.i), solar (a.ii), thermal (a.iii) and RF energy (a.iv), are analysed in the following sections.

i. *Kinetic energy harvesting*

Mechanical energy can be found almost anywhere that wireless sensor networks (WSN) may potentially deployed, which makes converting mechanical energy for instance from ambient vibration an attractive approach for powering wireless sensors. Mechanical energy harvesters are able to convert special kinds of mechanical energy, such as vibrations, rotation or motions, into electrical energy. There are many different options how to harvest mechanical energy, each of them based on slightly different physical phenomena. The most developed techniques are electromechanical transducers. This category includes electromagnetics, electrostatics and piezoelectric, which is probably the best developed technique for vibrational harvesting nowadays [4]. In the next subchapters, the above-mentioned principles of kinetic energy harvesting are introduced.

1. *Piezoelectric*

The most developed solution to convert vibration energy into electrical energy is based on the piezoelectric effect. Piezoelectricity describes the process of internal generation of electrical charge resulting from an applied mechanical force, illustrated in Figure 42. If force is applied on a piezoelectric crystal or fiber, the static structure is deformed, charge carriers are shifted and electrical current is generated [12]. The probably most famous usage is a lighter. By pressing on a piezo crystal, an enough high voltage is produced and a spark is generated which ignites the gas and creates a flame. In other words, a mechanical shock is converted into electricity, as shown in Figure 43.

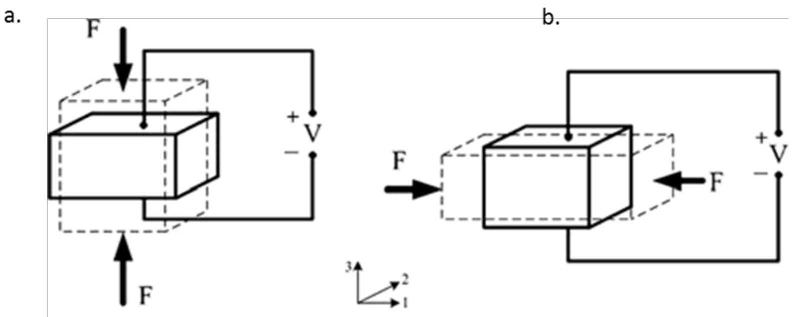

Figure 42: Piezoelectric generators: a. force applied form above; b. force applied from the side. Image taken from [72].

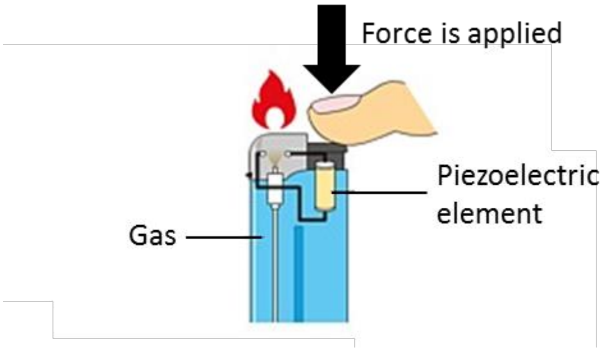

Figure 43: Working principle of a lighter. Image taken from [73].

Energy harvesting systems which do not rely on sudden mechanical shock make use of freestanding piezoelectric membranes or cantilevers and vibrational beams to pick up ambient oscillations.

2. *Electrostatic*

Electrostatic transduction is a promising way to convert ambient vibrations into electricity. Its operation is based on a capacitive structure created by two standalone electrodes. The gap between both electrodes can be filled with air, vacuum, or any dielectric materials [74]. By moving one of the electrodes, a variation of capacitance takes place, which can convert mechanical vibration to electricity by charge-discharge cycles or electret. For the energy harvesting technology only the electret-based electrostatic generators, which can directly turn ambient vibration to electricity enabled through the electret placed on the surface of one or two electrodes (see Figure 44). Electrets have a similar task than magnets in the electromechanic-based generators. In other words, electrets are the dielectric material with a capability of maintaining an electric field and surface potential inside the structure for years [75].

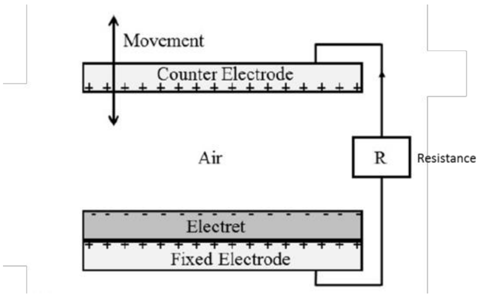

Figure 44: Schematic view of the electret-based electrostatic harvester. Image taken from. [75].

3. *Electromagnetic (EM)*

Electromagnetic induction was discovered by Michael Faraday in 1831. In an electromagnetic generator, strong magnetic fields are produced by permanent magnets and a coil is used as the conductor, which allows the flow of an electrical current in one or more directions. Either the coil or the permanent magnet is fixed to the frame while the other is attached to the moving part, respectively to the inertial mass. The vibration causes a relative displacement and thus the transduction mechanism starts working and electrical energy is generated [76] [77]. Figure 45 depicts two commonly seen examples of electromagnetic generators.

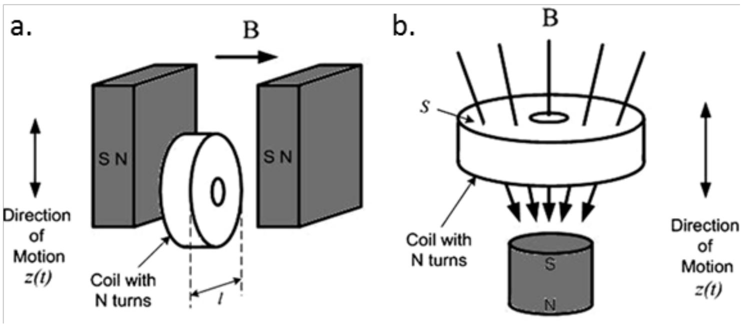

Figure 45: Electromagnetic generators. Image taken from [78].

Cepnik et al. [78] provided an informative report titled "Review on Electrodynamic Energy Harvesters – A Classification Approach", where many different electromechanical harvester prototypes are discussed in detail.

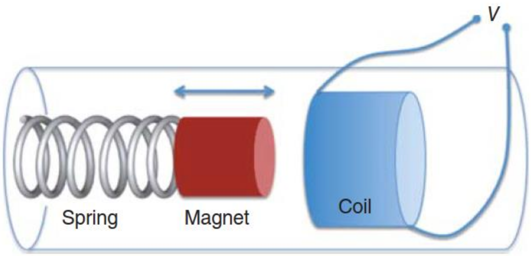

Figure 46: Basic scheme of an electromagnetic vibration harvester where a moving magnet oscillates with respect to a fixed coil. Image taken from [16]

4. Airflow energy harvesting

Using wind for the production of green and renewable energy is a well-known idea. Wind power will be one of the primary green energy source for the energy-starving world. But there is still a need for technical progress to implement airflow as energy source for IoT devices. There are several reports about airflow harvesters but still some fundamental research needs to be done due to current low conversion efficiency even at high wind speed and their relatively large sizes, which may be incompatible with many IoT devices [75] [79] [80].

Figure 47: Tex Energy's portable wind turbine Infinite Air for USB chargeable devices [81].

5. Emerging: Wiegand effect

The Wiegand effect, discovered by John R. Wiegand, is another possibility to harvest electrical energy from motion. It is a nonlinear magnetic effect, which is produced in specially annealed and hardened wires, called Wiegand wires. By causing the magnetic field of this wire to suddenly reverse, a sharp, uniform voltage pulse is generated. This pulse is referred to as a Wiegand pulse and can be used as a power source in energy self-sufficient devices, such as IoT edge devices. Sensors utilizing this effect require only a few simple components to produce sharply defined voltage pulses in response to changes in the applied magnetic field. Figure 48 illustrates, what such a sensor needs to function. Besides a short length of Wiegand wire, a sensing coil and alternating magnetic fields that generally are derived from small permanent magnets is needed [82].

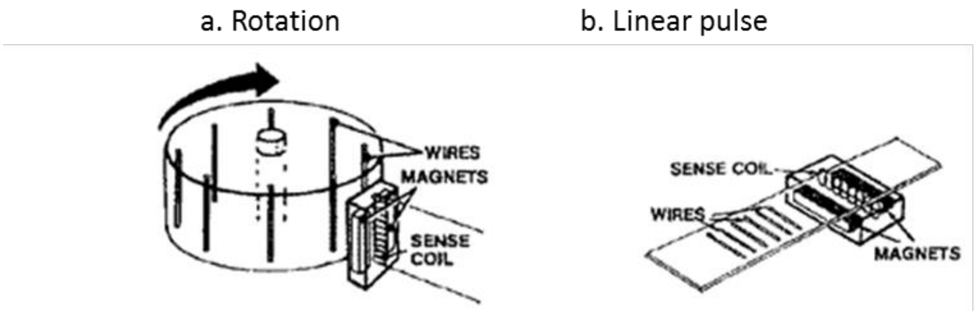

Figure 48: Two different Wiegand wire examples. Kinetic energy by rotation (a.) and linear pulse (b.) Image taken from [82]

6. Emerging: Triboelectric Nanogenerator (TENG)

"A triboelectric nanogenerator is an energy harvesting device that converts the external mechanical energy into electricity by a conjunction of triboelectric effect and electrostatic induction. This new type of nanogenerator was firstly demonstrated in Prof. Zhong Lin Wang's group at Georgia Institute of Technology in the year of 2012. As for this power generation unit, in the inner circuit, a potential is created by the triboelectric effect due to the charge transfer between two thin organic/inorganic films that exhibit opposite tribo-polarity; in the outer circuit, electrons are driven to flow between two electrodes attached on the back sides of the films in order to balance the potential. Since the most useful materials for TENG are organic, it is also named organic nanogenerator, which is the first of using organic materials for harvesting mechanical energy" [83].

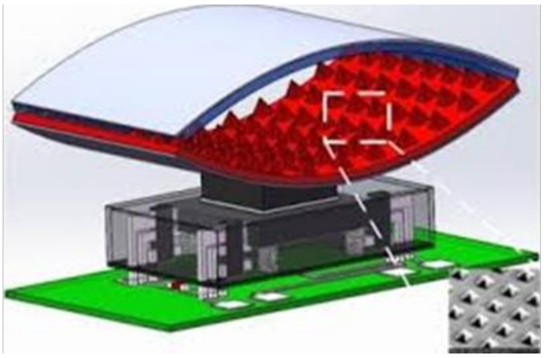

Figure 49: Tribolelectric nanogeneraor. Image taken from [84]

It was announced that a first commercial product using TENG shall be launched between the end of 2017 and the beginning of 2018.

ii. Light energy harvesting

Most of the energy, which is used by humans, such as oil, coal and gasoline, originates indirectly from sunlight. Sunlight is also the best energy to be harvested, if it is available as energy source. The average power density of outdoor sunlight is 100 mW/cm^2 under AM 1.5 illumination spectrum. Indoor light depends on e.g. the type, size and the position of light source and may vary widely, from 0.1 to 1mW/cm^2 [85]. The next subchapter explains how light can be converted into electrical energy.

1. *Photovoltaic cell*

Photovoltaic (PV) cell, also known as solar cell, is by far the most highly developed electrical device that converts the energy of light directly into electricity by the photovoltaic effect. There are various solar cell technologies, with a history of more than 50 years [86]. The photovoltaic effect refers to photons of light exciting electrons into a higher state of energy, allowing them to act as charge carriers and generate an electric current. As shown in Figure 50, a PV cell contains two different layers. n-type silicon layer, which has free electrons, and p-type silicon layer, which is missing electrons, leaving "holes" in their place. When these two materials are placed side by side inside a solar cell, the n-type silicon's spare electrons "jump over" to fill the gaps in the p-type silicon. This means that the n-type silicon becomes positively charged and the p-type silicon indicates a negative charge. Thereby, an electric field is generated and electric current is provided.

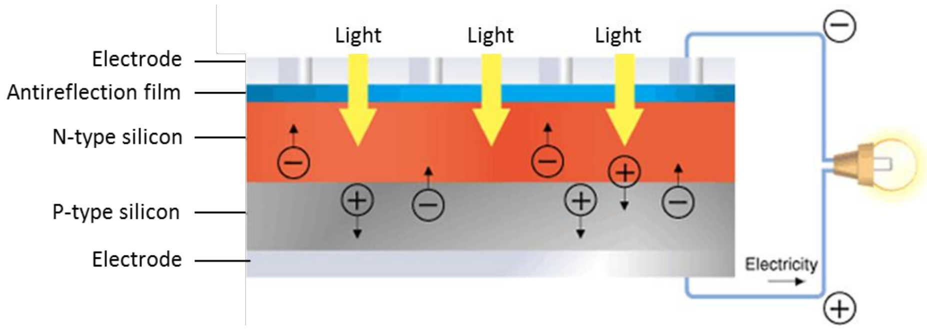

Figure 50: Simplified working principle of a photovoltaic cell. Image taken from [87].

The efficiency varies enormous based on the technology used for the PV cell. There is an overview given (Figure 51) from the NREL (national renewable energy laboratory) based in USA, which illustrates the different technologies and above all the improvements in efficiency of PV in recent years. There are four categories:

- Multi– and single-junction cells
- Crystalline Si Cells
- Thin-Film Technologies
- Emerging PV

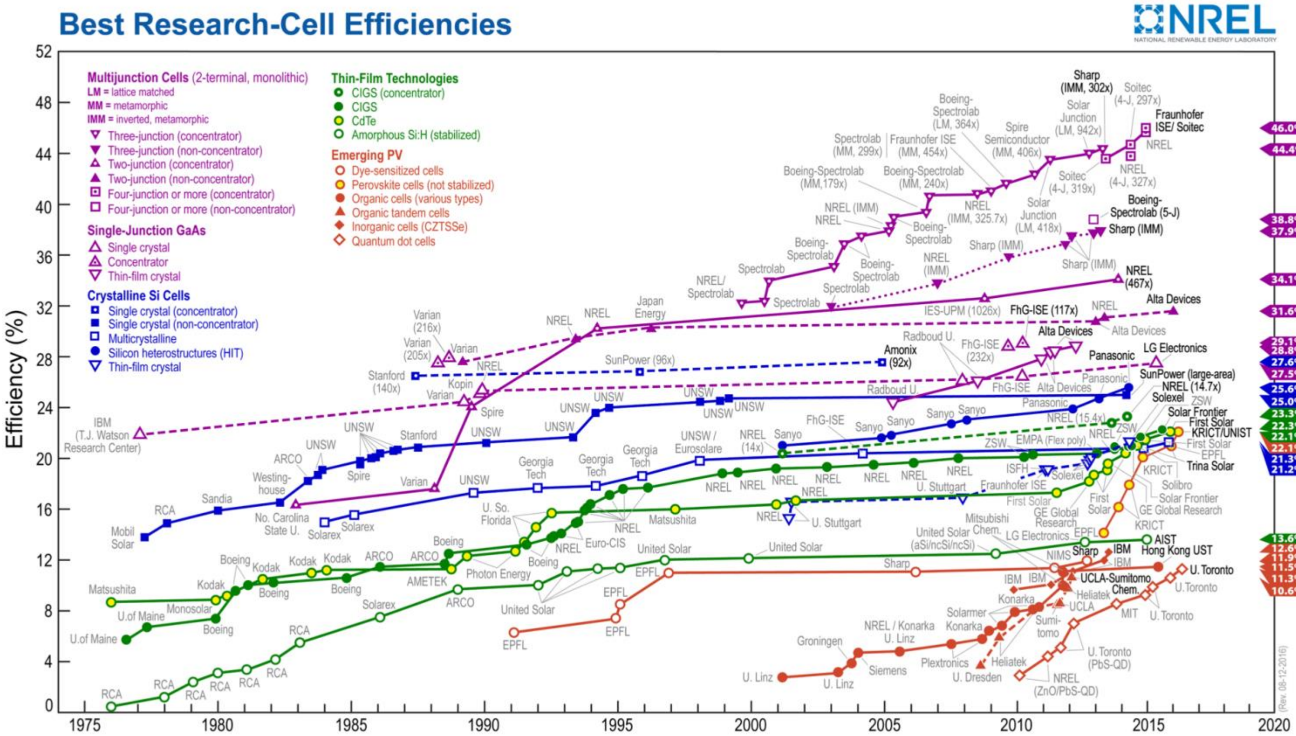

Figure 51: Increase in efficiency in recent years of PV cells based on different technologies. Image taken from [88].

2. *Emerging: LED and Photodiode energy harvesting*

Instead of using relatively expensive PV cells, considerably less expensive LEDs and photodiodes can be used to harvest light energy and produce electrical energy. LEDs are light diodes, for instance semiconductor components, that normally emit light but that are also able to capture light. A tiny amount of electricity flows between the component's leads, which can be harvested and used for the generation of a few microjoules, which could be enough to supply low-power devices, such as IoT edge devices. Photodiodes supply more energy compared with LEDs, but they are more expensive [89].

iii. Thermal energy harvesting

Almost every system loses heat as waste energy. This includes all kind of industries, transportation, human body and many more. Depending on the application area the power density varies from 2 to 600 μW/cm^2. Existing energy harvesting techniques using thermal energy are based on the thermoelectric and pyroelectric effect, which are both described in the next two subchapters.

1. Thermoelectric effect

The thermoelectric effects describe the interaction between heat and electricity. Thermoelectric devices make us of the Seebeck effect to generate power from a temperature gradient. The Seebeck effect arises due to the fact that charge carriers in metals and semiconductors are free to move. When a temperature difference (ΔT) is applied to this type of materials, the charge carriers will diffuse from the hot to the cold side producing and electrostatic potential (ΔV). Thermoelectric generators (TEG) are composed by multiple thermocouples, of p- and n- type materials connected electrically in series and thermally in parallel. When exposed to a temperature gradient, the carriers with either positive or negative charge, flow from the hot top to the cold bottom (heat flow) and induce and electrical current due to movement of the charge carriers (current flow), as illustrated in Figure 52. The voltage of each element (p- and n-type) is added together [4] [90] [91].

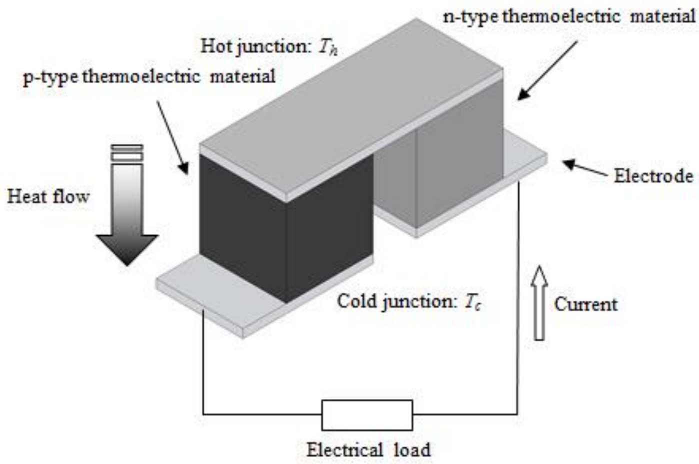

Figure 52: Schematic figure of a thermocouple with a n-type and p-type leg. Image taken from [92]

2. Emerging: Pyroelectric effect

As mentioned above, thermoelectric materials and systems generate electrical power from temperature gradients, while pyroelectric materials produce power from temperature fluctuations and have some similarities to the way in which piezoelectric harvester convert mechanical oscillations into electricity. Pyroelectric conversion techniques have been under investigation for over 50 years, but it has not received the same amount of attention compared with thermoelectric energy harvesting techniques during this time period [93]. Nonetheless, Hunter et al. presented that pyroelectric techniques can be cost competitive with thermoelectric and published a pyroelectric generator illustrated in Figure 53. It still needs some improvements for practical applications.

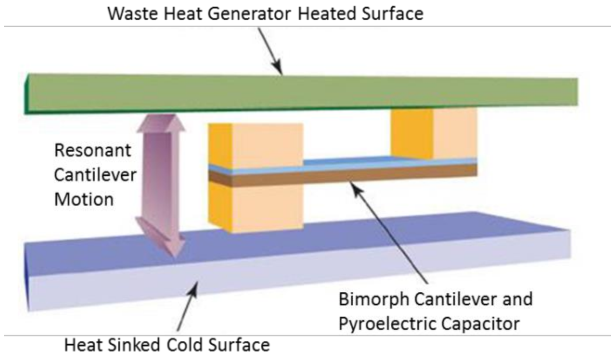

Figure 53:Pyroelectric generator; thermo-mechanic oscillator. Image taken from [93].

iv. Radio frequency (RF) energy harvesting

The RF spectrum is part of the electromagnetic (EM) spectrum and ranges from 3 kHz to 300 GHz. The biggest advantage of RF radiation as energy source is its abundance. Every urban region is covered by radio, television broadcasts, mobile telephone services and wireless local area network (WLAN), which makes RF radiation a very attractive ambient energy source. Wireless energy harvesting (WEH) has proven to be one of the most promising solutions because of its simplicity, availability and ease of implementation. The WEH receives the transmitted radio waves with an antenna and converts the received RF energy into a stable direct current (DC) energy source to supply the sensor device [15]. The harvested RF power can generate about 1.8-4 V with a total converted power of about 100mW [10].

Annex E Lists

a. Lists of Figures

b. List of Tables

c. Bibliography

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