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European Commission

Business Innovation Observatory

Clean Technologies

Energy harvesting

Case study 32

Enterprise and Industry

Clean Technologies

Energy harvesting

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1. Executive summary

Energy harvesting (EH) is the process by which minute amounts of energy from one or more of naturally-occurring energy sources are captured and stored.[1] This energy can take the form of vibration, temperature differences, light, or magnetic forces. The most promising technologies for harvesting energy from these sources are piezoelectric materials (for mechanical energy) and thermoelectric/pyroelectric materials (for thermal energy).[2]

Energy harvesting technology has already been used for decades in everyday applications, such as in bicycle dynamos. Nowadays, the technology is spreading to more and more application areas, and is of particular interest for application in wireless sensors. These sensors are often incorporated in completely wireless networks, the type often used to collect data and automate specific processes. Building automation and industrial automation, as well as smart homes and security systems are currently lead markets for the application of wireless sensor networks.

The benefits of applying energy harvesting technology in wireless networks are substantial. By powering a network with an energy harvester instead of a battery or wired connection, its associated maintenance and installation costs are greatly reduced. This opens up new possibilities to install wireless sensor networks for data collection in all kinds of application environments. Widespread installation of wireless sensor networks facilitates new technology trends such as the Internet of Things and Big Data collection and analytics, which in turn can help to optimise a great variety of processes, including traffic management and wild fire detection. Finally, by using ambient energy which is otherwise wasted, energy harvesters reduce energy consumption and associated carbon emissions.

Challenges associated with implementing energy harvesters for wireless networks relate to conservatism and technology readiness. Some industries are conservative towards adopting this new technology, choosing to wait for hard evidence that the technology can operate without failure for several years. It is therefore hard for companies that sell energy harvesting solutions to find launching customers. In addition, the electric currents harvested sometimes can be too weak to power wireless networks on remote locations or in extreme environments, somewhat limiting the application possibilities of energy harvesting on wireless networks.

Policy makers can help to capitalise on the benefits and tackle challenges for uptake of energy harvesting solutions by acting as a launching customer. Energy harvesting solutions could be made a mandatory part in public procurement. In addition, government could generate strong signalling effects towards customers by facilitating procedures for minimum quality and safety standards of energy harvesting devices.

2. Energy Harvesting

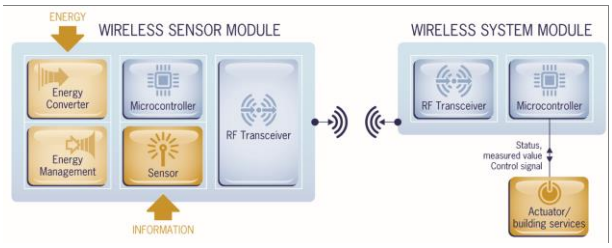
Energy harvesting technology facilitates a process in which (often) small amounts of energy, which can manifest in different forms, can be transformed into an electrical current and stored for later usage. The most common energy sources used for energy harvesting include:

- mechanical energy in the form of for instance vibrations or pressure;
- thermal energy in the form of ambient temperature differences, waste heat or friction;
- light energy in the form of sunlight or room lighting;
- electromagnetic energy produced by inductors, coils and transformers;
- other forms of naturally occurring ambient energy such as wind, water flow, ocean currents, but also energy generated by humans and other living creatures.

Energy harvesting technologies are currently already applied in everyday products, e.g. in kinetic wrist watches that use body movement to wind a spring and store energy, or in bicycle dynamos that use wheel movement to generate an electrical current. The foundations for these inventions were already laid in previous decades and centuries, and are no longer considered revolutionary. In this report we therefore focus on a new application domain for energy harvesters, specifically as power sources for wireless sensor networks. These networks are applied for instance in buildings and on manufacturing plants to collect data and automate specific functions.

This application of energy harvesters is currently entering markets such as building and industrial automation, smart homes, and security systems. Energy harvesting technology rarely operates in isolation. A bike dynamo does not provide much benefit without the lamp it is connected to. The same goes for wireless networks. Key components in such a system include an energy converter (the harvester), a low-power energy management controller, a sensor or other measurement device, and a radio frequency transceiver (Figure 1).

Figure 1: Key components of energy harvesting powered wireless networks



Source: Courtesy by EnOcean

The most promising technologies for harvesting energy for wireless network purposes are piezoelectric materials, which harvest mechanical energy, and thermoelectric or pyroelectric materials, which harvest thermal energy.

The benefits of energy harvesting solutions are numerous, yet some are more evident than others. Evidently, energy harvesting applications can help to engage the global energy demand, by capturing otherwise lost energy. This is beneficial both for the environment and for the financial performance of companies and households. Therefore, energy harvesting technologies are currently also deployed to improve the energy efficiency of household and office devices.

In addition, energy harvesting solutions provide increased freedom to product designers. Devices can become ever smaller, as there is need neither for a voluminous battery, nor for a power cord. This wireless feature allows energy harvesting applications to power equipment and installations at remote locations, without connecting to the main power grid. More localised power generation reduces the need for expensive power distribution grids.

Finally, energy harvesting solutions help to power the minute devices that are rapidly spreading as a result of trends such as the Internet of Things. The reduced installation and maintenance cost of energy harvesting applications mean that wireless networks become economically interesting to install. Other characteristics of these applications include a self-sustaining energy source, practically infinite lifetimes, provide untethered mobility, cooperate at signal and energy levels, and facilitate synergistic distribution of information and energy in networks.

3. Socio-Economic Relevance

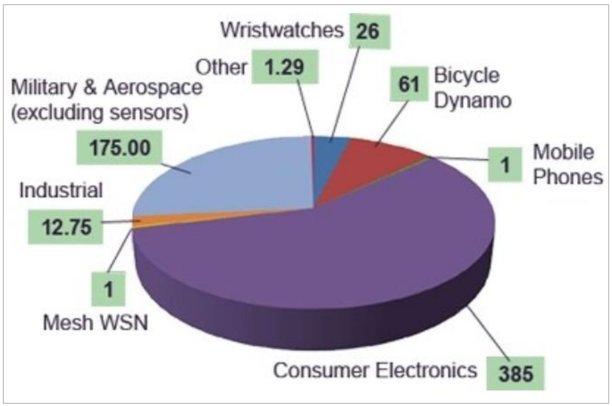
The socio-economic relevance of energy harvesting technologies is relatively straightforward, with an estimated market potential of EUR 3 billion in 2020 and ample opportunity for job creation. Moreover, wireless sensor networks powered by energy harvesters are relatively easy to install, hardly require maintenance, and reduce energy consumption, while the data they generate can be used to optimise all kinds of processes, from wildfire detection to building automation.

3.1. The market potential of the trend

In 2009, the overall market for energy harvesters amounted EUR 463 million, with 67% being incorporated in consumer goods. For 2011, this number had grown to EUR 530 million, with almost EUR 11 million being spent on energy harvesters in wireless sensor applications.

In 2011, most of the harvesters used in the market segments displayed below (Figure 2: Division of energy harvester applications per product segment in USD of revenues (2011)) were solar cells, followed by electro dynamos, which together are among the most mature energy harvesting technologies. However, promising new technologies are now starting to capture market share, enabling the powering of machines and equipment in areas where this was not possible before.

Figure 2: Division of energy harvester applications per product segment in USD of revenues (2011)



Source: EE Times website on 'Energy harvesting could reach a USD 4.4 billion market in 2021[3]

Energy harvesting, in terms of number of organisations involved, is mainly a European and North American affair. However, a small number of very large organisations in East Asia have large budgets appointed to the development of energy harvesting technologies.

Prospected numbers on the size of the energy harvesting market by 2017 to 2019 vary somewhat. According to the Energy Harvesting Journal, the energy harvesting market is expected to grow to over EUR 3 billion annually by 2019, driven by energy harvesting for consumer products. By 2040, energy harvesting, using existing and emerging technologies, will likely be incorporated in almost all manufacturing processes and manufactured devices.[4] This number is confirmed by two other reports which also forecast the market for energy harvesters to reach the EUR 3 billion mark around 2020.[5,6]

Analysts at Yole Développement are more conservative and forecast energy harvesting for the wireless sensor network market to approximate EUR 190 million by 2017. Fastest growth in this market segment is to be expected from thin-film thermal technologies and from demand for wireless networks for the building and industrial sectors.[7]

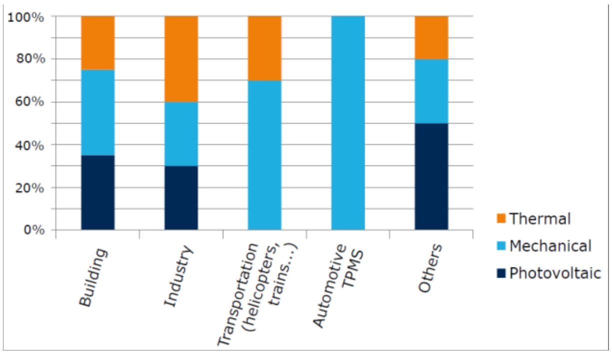
Technological developments, both in low power electronics and in communication protocols, are enabling wireless sensor networks to be autonomously powered by energy harvesting technologies. It is expected that technological development and market demand will focus on energy harvesting applications that operate between the ranges of tens of microwatts up to tens of milliwatts. Pulse, solar, and thermal harvesting is particularly useful for the automation of buildings, whereas vibrational and thermal energy will mainly be used for industrial applications.

The biggest cost saving potential of energy harvesting applications is expected to be realised in building automation. This is a promising lead market for energy harvesting technology, as elimination of copper wiring in new and existing commercial buildings, combined with savings in both installation, maintenance, and materials costs are creating huge market potential in this sector. In addition, the required infrastructure, standards, and components suppliers are currently in place. The building automation market currently accounts for almost all commercial energy harvesting business activities, with sales approximating two million energy harvesting units in 2011. This market is expected to grow tenfold towards 2017, when it is expected to still make up more than half of the total energy harvesting market.

The other major energy harvesting market that is currently developing is that of industrial wireless sensor networks for monitoring industrial processes and equipment condition. It is expected that growth will pick up substantially from 2015 onwards. Prices of key low-power wireless components and communication protocols will go down and will become accepted by industry. Currently, the oil and gas industry are the lead segment in this market, and they are using expensive electromagnetic vibration harvesting devices for high-value installations operating in extreme or remote environments.

In parallel, markets for wireless home automation, sensing equipment for logistical applications, and medical implants (particularly pacemakers) will likely develop further towards 2020. Figure 3 below provides a breakdown of energy harvesting sources for several lead markets. Table 1 below provides an overview of the company cases referred to in this case study report.

Figure 3: Breakdown of the key energy harvesting sources per application market by 2017



Source: Analyst Corner, Energy harvesting market will approach USD 250M in five years, with fastest growth from thin film thermal technologies, October 2012, issue number 12[8]

Table 1: Overview of the company cases referred to in this case study

Company	Location	Business innovation	Signals of success
Pavegen	UK	Pavegen has pioneered a floor tile which translates the energy from pedestrian footsteps into energy which can be used for powering traffic lights and other applications.	Pavegen already serviced a substantial number of customers. The technology is already installed in 14 countries in schools, shopping centres etc. Massive blue-chip companies like Shell, Schneider electric and Siemens have shown interest for an experimental installation. Pavegen currently focuses on bigger clients, to promote the brand and spread the message. Pavegen is currently aiming at large infrastructure projects. This year the technology will be installed in Europe's largest airport and in one of London's largest shopping centres.
EnOcean	DE	EnOcean is the originator of patented energy-harvesting wireless sensor technology for use in building and industrial applications as well as in further application fields such as home, smart metering, logistics or transport.	EnOcean has won several prizes since its start in 2001. These include the Bavarian Innovation Prize 2002, the award "Technology Pioneer 2006" by the World Economic Forum, the "Top-10 Product for 2007" award by Building Green, and was among the Guardian Global Cleantech top 100 in 2011. More than 100 leading integration partners (OEMs) all over the world have adopted patented EnOcean technology to create and manufacture products for very different applications, e.g. building automation and industry.
Micropelt	DE	Micropelt has developed both thermoelectric and inductive energy harvesters. The former uses temperature differences to generate electricity and transmit vital data to outside receivers, and can be installed on individual radiators to regulate room temperature. The latter converts magnetic energy and can be installed power distribution systems.	Micropelt introduced its intelligent thermostatic radiator valves (iTRVs) at the light and building show in march this year. The unit will go in production this summer and we will be shipped to customers for the winter 2014/2015 season. The coming "heating season" will be used to provide end customers with the opportunity to test the devices and convince them of its benefits. It is expected that next year, summer 2015, larger quantities can be manufactured and shipped. This version will be a standalone version, which can easily be programmed using a smart phone or Wi-Fi router.
Voltree	USA	Voltree has developed a patented bioenergy harvesting technology which converts the metabolic energy of trees to usable electricity, based on the pH-difference in the tree and the soil. The current can be used to power sensors that collect data for forest fire prediction, environmental and agricultural monitoring, and homeland security purposes.	Voltree acquired substantial media coverage (including from CNN) after its research results were published through MIT. The company won the "Best of What's New Award" in 2009. The company is currently offering several sensor products with autonomous powering through a combination of several energy harvesting technologies. The company has, however, also experienced the limitations of energy harvesting potential for extreme or remote locations.

Company	Location	Business innovation	Signals of success
NikkoIA	FR	NikkoIA uses new photo-detection materials that are deposited as a thin film layer onto semiconductor substrates. The photo-detection material is sensitive to visible and infrared light and generates an electrical signal based on the infrared light it absorbs. The electrical signal is read by the substrates and can be used in security, medical imaging and user-interface applications.	NikkoIA was founded in 2011 as a spin-off from Siemens, and is currently part of an FP7 collaborative project to develop organic semiconductors for near infrared (NIR) optoelectronics. The company will benefit from EUR 1.5 million in subsidies over the next two years as a result of participation in several EU funded collaborative development projects it joined in 2013.[9] NikkoIA and Siemens AG have signed a worldwide and exclusive license agreement on an extensive patents portfolio, either already granted or in the process of being so. This agreement is completed by a transfer of technology and know-how from Siemens AG to NikkoIA SAS to speed up the industrialisation phase of the newly developed photo-detection material.

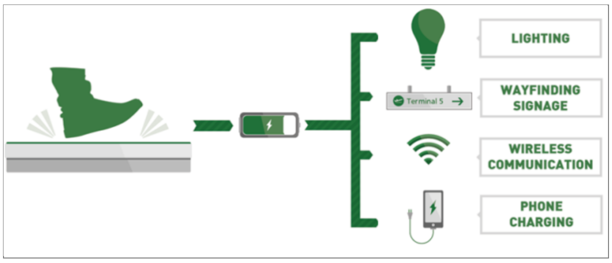
3.2. Technological solutions of leading companies offering Energy Harvesting Solutions

Problem 1 – While Pavegen's CEO was conducting an internship for his university study at a big energy company, the urbanisation and renewable energy trend were already emerging. Renewable sources like wind and solar energy were less suitable for dense urban areas, due to high building density. This is why he started experimenting with the concept of footfall energy regeneration.

Innovative solution 1 – After his internship, Pavegen's CEO went back to university to crack the code of how footfall energy technology could be developed. The result of this is currently being commercialised through Pavegen. Pavegen has pioneered a floor tile which translates energy from pedestrian footfall into energy which can be used for powering traffic lights or build-in wireless sensing technology. This sensing technology can collect and distribute information on pedestrian traffic at high density junctions, and can even make a connection to social media. This is valuable information to traffic management at for instance airports or to marketers at shopping malls. These locations could really benefit from crowd management and, to a lesser degree, energy savings.

Pavegen technology is also installed at schools to raise awareness on sustainability. The installation, which features tiles and a signalling device similar to traffic lights that displays when energy is generated, is an extremely engaging renewable energy source for children that cannot resist its colourful lure.

Pavegen's footfall energy harvesting technology can be used to power various applications, as shown in the figure below.



Source: Pavegen website – technology section[10]

Problem 2 – EnOcean is a venture-funded spin-off company of Siemens AG, founded in 2001. The core technology applied by EnOcean was invented more than thirteen years ago within Siemens. The Idea was to power wireless sensors with ambient energy. The company positioned the technology as batteryless wireless radio. However, the energy harvesting technology does not function in isolation. For EnOcean's technology to be applied for various purposes and add value to its customers, it needed to be linked with wireless sensors, a data transmitter and power management module.

Innovative solution 2 – To get its energy harvesting technology to the market, EnOcean formed an alliance of Original Equipment Manufacturers (OEMs) for building automation equipment (the EnOcean Alliance). These OEMs are the key partner in the value chain for building automation. Together they developed an international wireless standard protocol optimised for energy harvesting that covers architecture and lower layer protocols. This was one of the most important success factors for the adoption of EnOcean's technology. The EnOcean Alliance's efforts have standardised demand for wireless building automation equipment.

EnOcean modules combine micro-energy converters with ultra-low power electronics and reliable wireless communications. This enables EnOcean customers to create self-powered wireless sensor solutions that are fundamental for efficiently managing energy in buildings and industrial applications.

EnOcean technology allows fast development and marketing of new wireless solutions in building services, industry and other sectors. Standardised sensor profiles make for interoperability of the resulting products. Devices from different manufacturers can now communicate and cooperate with one another in one and the same system (figure 5).

EnOcean's Dolphin System Architecture, which allows fast development and marketing of new wireless solutions in building services, industry and other sectors.

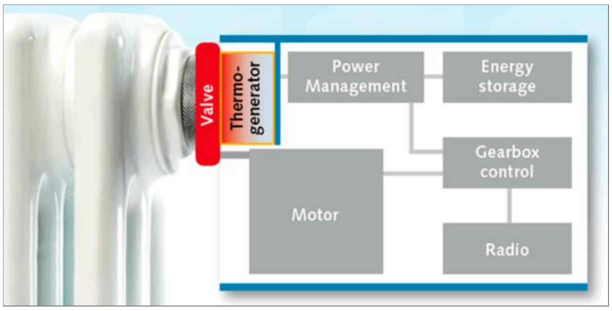
Source: EnOcean website - EnOcean Dolphin System Architecture[11]

Problem 3 – The thermal energy harvester idea, on which Micropelt's technology is based, was already developed by several thermal electric researchers in 1998. The initial target application for the technology was not energy harvesting, but cooling. It was invented for microprocessor cooling applications. This is also the market that Micropelt initially targeted to sell its technology on. However, chip cooling is a difficult market to compete in. At a certain point, one of the largest potential customers in this market, Intel, decided to move to multicores, to solve the heating problem for microprocessors.

Innovative solution 3 – Due to the difficulties with accessing the chip cooling market, Micropelt started to think about different application areas for its technology. Micropelt's founders realised that its technology featured two operating models. By exposing its thermo-generator to temperature differences, it could generate electricity. In 2007, Micropelt decided to start researching potential energy harvesting applications for its technology. By combining the energy harvesting potential with wireless sensing technology, the company is now able to offer maintenance free applications to both industry and consumers. Micropelt currently focuses on the oil and gas industry. Its mNode product measures temperature in installations where wiring is extremely expensive. Preventing meltdown is therefore crucial. In addition, adding more wired sensors substantially increases costs. Installation costs of Micropelt products are low and the devices are almost maintenance free, as the sensor is autonomously powered over its full lifetime.

Mr Volkert, Micropelt's CEO, grew-up in a family with a heating business. He is familiar with this sector and is currently finalising the design and production of an application for smart buildings and homes. The application allows users to automatically set temperatures of individual radiators (figure 6 illustrates the key components).

A schematic overview of Micropelt's key product features for heating in smart buildings.



Source: Micropelt website – Radiator Valve iTRV[12]

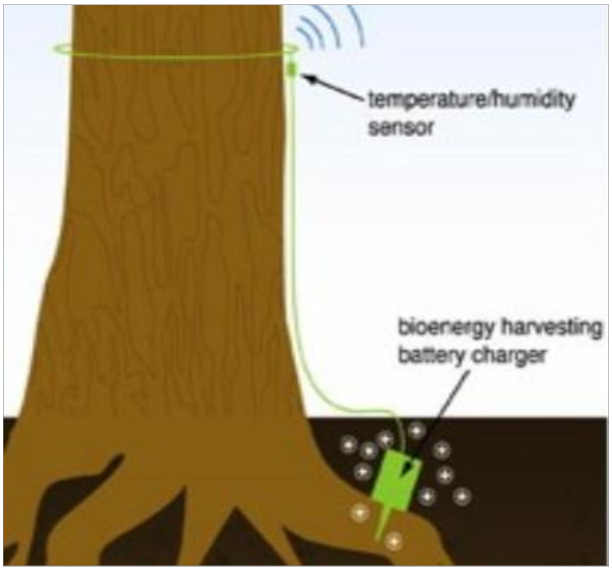
Problem 4 – MagCap Engineering is a manufacturer of custom transformers and power supplies for radar and microwave equipment. In 2005, this company was approached by an inventor who wanted to have a custom circuit with an undisclosed power source designed, under the precondition that the company's engineers would sign an NDA. In exchange for this work, MagCap would become 50% owners of the new technology. MagCap's founder and owner Stella Karavas decided to take up the challenge. After designing the custom circuit and testing the device by hooking it up to a tree, MagCap's engineers found out that it was producing a small but measurable direct current. The only problem was that the engineers did not know how the device was able to produce this current (see figure 7).

Innovative solution 4 – Stella Karavas eventually ran into a postdoctoral researcher at MIT named Andreas Mershin, who was able to harvest energy from spinach. MagCap and MIT decided to have a student conduct laboratory tests to uncover the origin of the current produced by the custom circuit when connected to a tree and the soil (funded by MagCap). Results of these experiments showed that the current was produced as a result of the difference in pH (acidity level) between the tree tissue and soil.

In 2005, still before the laboratory experiments, Stella Karavas and MagCap's president Chris Lagadinos founded Voltree. Voltree would become the owner of the energy harvesting technology, and the vehicle for commercialisation. Voltree made solid progress on a system of small tree-powered sensors designed to be placed in fire-prone national forests, where they could monitor temperature and humidity and radio the data back to remote automated weather stations (RAWS) operated by the U.S. Forest Service.

Initially, the technology was intended to function as a Mesh wireless network for forest fire detection. In a mesh network each mesh node (in this case a tree equipped with an energy harvester, sensor and RF transmitter) relays data for the whole network. All nodes cooperate in the distribution of data in the network. The electrical current generated by trees is very low. This in combination with the huge distances to be covered (in forests) and elements like foliage disturbing RF transmission meant that it was hard to maintain connection between all nodes. As a result, measurements could become inaccurate with potentially disastrous results for forest fire prediction. This is why Voltree has moved away from mesh wireless applications. Energy harvesting technology is not (yet) suitable for powering mesh wireless networks in remote or extreme locations.

Voltree Power's patented bioenergy harvester converts living plant metabolic energy to electricity, providing a battery replacement alternative for ultra-low power sensors to monitor for instance forest conditions.



Source: Voltree Power website – Bioenergy Harvester[13]

Problem 5 – Current photo-detection sensors used in markets which NikkoIA is targeting, e.g. identification and authentication for high security applications like secure payment or border monitoring, are often bulky and too expensive for global deployment.

NikkoIA's novel photo-detection material based products enable more intuitive, less invasive, flexible and affordable systems and solutions for identification in the medical, security, and user interfaces markets.[14]

Innovative solution 5 - NikkoIA uses new photo detection material which is applied as a thin film layer onto industry-standard electronic reading substrates (e.g. semiconductors able to process the electronic current generated as an output). The photo detection materials, by harvesting certain wavelengths of light, function as high-performance and cost-optimized sensors. The shape of the sensor can easily be adjusted in size, shape, sensitivity and resolution.[15]

The photo detection material is receptive to visible and infrared light and generates an electrical signal based on the harvested infrared light. It is made of both organic and inorganic components sensitive to specific wavelengths and can be easily adjusted by modifying the nature and mix of these components. Depending on the need of the application, this enables great sensitivity either to a specific wavelength of light or to a large range of wavelengths from the visible and near infrared spectrum.

The electrical signal is processed by a transistor or semiconductor, on which the photo detection material is applied. The material is deposited by extremely simple, mature and robust processes such as spray or spin coating, which ensures cost-efficiency and interoperability with the latest electronic substrate developments.

This new technology enables competitive solutions compared to current technology (InGaAs-based, which is an alloy of three chemical compounds) and opens new opportunities for near infrared image sensors.

NikkoIA's flat, scalable and multispectral sensors allow the design of simpler, cheaper and more robust systems for multimodal identity identification.

Source: NikkoIA[16]

3.3. The creation of new markets and jobs

Although energy harvesting solutions partially replace existing jobs that, for instance, focus on manufacturing or maintenance of battery powered or wire powered sensing applications, they are also enabling new application domains for measurement equipment or autonomous systems.

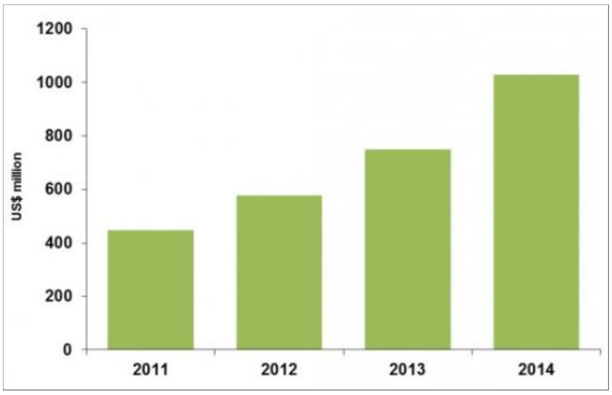
Leading energy harvesting companies in Europe are still relatively small with regards to the number of people they employ. For example, EnOcean, the world's largest supplier of energy harvesting powered wireless sensor networks, employed around 60 people in 2010.[17] However, trends like Big Data analytics and the Internet of Things, (partially) enabled by energy harvesting technologies, are associated with substantial job creation. Gartner for instance reports that by 2015, 4.4 million IT jobs will be created to support Big Data analytics.[18]

Energy harvesting technology facilitates the rapid spread of minute devices that are connected to the Internet of Things by providing them with an autonomous power supply. As the installation and maintenance costs of these (sensing) devices are drastically reduced, their deployment increasingly becomes economically interesting. By facilitating widespread data collection, energy harvesting solutions are powering disruptive concepts like the Internet of Things and Big Data analysis, creating new high skilled jobs in for instance data analytics, forecasting and performance improvement.

Energy harvesting can also bring solutions to remote locations or developing markets, which e.g. Pavegen is aiming to access in the near future. The energy harvesting aspect is particularly interesting for these countries. Many cities in developing countries experience load shedding (sharing electrical power capacity between cities or parts thereof). Pavegen technology can be used to power key infrastructure like traffic lights during blackout periods. The same holds for remote areas in developing countries that are not connect to the central power grid at all.

As mentioned in the introduction of this case study, the market for wireless sensor networks is driven by the application of energy harvesting technology. This new lead market for energy harvesters (new because the technology is already around for decades) is expected to grow from USD 0.45 billion in 2012 to USD 2 billion in 2022.[19] Currently, the market potential of wireless sensor networks is approximately USD 1 billion (Figure 4).

Figure 4: Development of the total market for wireless sensor networks, a lead market for energy harvesting applications, in USD millions.



Source: Wireless Sensor Networks (WSN) 2012-2022: Forecasts, Technologies, Players[20]

The lead segment within the market for wireless sensor networks is building automation. Building automation applications as enabled/offered by EnOcean or Micropelt open up new possibilities for building renovation, which previously would not have been economically possible. As installation and maintenance costs of wireless automation hardware powered by energy harvesting are much lower, it might become interesting to decrease energy consumption in existing real estate.

3.4. Client perspectives and challenges related to the uptake of the trend

Pavegen's first product was sold for 5,000 pounds (approximately EUR 6,300) to a person in the CEO's network, which wanted to support the company towards commercialisation. The first experimental installation at the CEO's former elementary school generated a lot of publicity. This created enough momentum for the company to acquire new commercial leads.

Currently, Pavegen's technology is mostly in demand for its awareness/promotion potential. Customer companies love to use it to promote their sustainable image, and policy makers deploy it to generate awareness for renewable energy solutions amongst citisens. However, Pavegen's greatest added value lies in the self-powered wireless sensing technology that is incorporated in the energy harvesting installation. This provides valuable insight into traffic movements, which can be used for crowd management that aims for increased safety at for instance busy airports or large sporting events. In addition, marketers can use the information to better facilitate shopping behaviour near busy malls or increase exposure of advertisement.

The biggest barrier to uptake of Pavegen's technology is that it is currently still more expensive than conventional floor tiles. The company is pushing hard to reduce production costs, to eliminate price from the equation. The same goes for silicon wafer-based energy harvesters like those of Micropelt. This technology can only be produced cost-efficiently when it is manufactured in high volumes. The company therefore identified application domains with high customer benefits, substantial and stable temperature differences, and potential for application in large scale or in high volumes.

For Micropelt and EnOcean, conservatism within the industrial sector and the building automation sector poeses a key barrier to adoption. In building and industry markets, value chain actors typically are very conservative. The installer, specifier, or system integrator tends to approach new technologies with a risk-averse attitude, preferring evidence that the technology will function for five years without failure.

The acceptance of wireless technology in general took years. Industry demands failure-safe installations and accurate measurement equipment. Wireless technologies are associated with security issues and an unstable power supply as a result of energy harvesting instead of wired or battery powered devices, and with inaccurate measurements.

"Customer companies love to use our technology to promote their sustainability image and policy makers deploy it to generate awareness for renewable energy solutions amongst citizens." – ***Pavegen***

For EnOcean it was crucial to find a launching customer for its building automation applications. According to EnOcean's Chief Marketing Officer this so called 'use case' can subsequently be used to prove the technology's benefit and convince other customers of adopting the application. For EnOcean this launching customer was a facility manager at Bosch Siemens Hausgeräte. The energy harvesting powered automation hardware fitted perfectly with the customer's desire to arrange its building according to Feng Shui principles (slim partitioning walls without room for wired automation equipment).

Adoption of Voltree's initial application also faced issues with regards to inaccurate and unreliable measurements. The technology was initially aimed to function as a mesh network for wildfire detection. However, this combination proved to demanding for the challenging environment in which the energy harvesting device had to operate. A mesh network's accuracy and reach is dependent on the number of nodes that accurately measure and transmit information to the next node in the network. A forest, however, is an extremely challenging environment for RF transmission due to the density of foliage, resulting in blind spots or inaccurate readouts. This in combination with the high-impact/risk application of wildfire detection meant that Voltree's initial application was not suitable to its target market.

4. Drivers and obstacles

There are some evident drivers for the diffusion of energy harvesting solutions, which positively affect all clean tech markets, such as the rate of climate change and increasing resource scarcity. Other drivers originate from the fact that energy harvesting can be seen as an enabling technology for many new applications like wireless networks, underlying the global trends of the Internet of Things and Big Data. As energy harvesters do not offer any true benefit in isolation, interoperability between system components and collaboration between vendors in the value chain are crucial factors for success.

4.1. Technological developments like the Internet of Things and Big Data

Developments within the domain of Big Data and the Internet of Things are driving the need for low-maintenance autonomously powered wireless sensing equipment. These features are enabled by energy harvesting technologies. Companies are more and more interested in collecting and analysing all kinds of real-time customer data. This is a big trend in which for instance most of Pavegen's partners are very much interested in. Companies would like to use the data Pavegen's technology collects on traffic movements to study consumer behaviour around shopping malls, to increase advertisement exposure, to provide way-finding solutions, or to enhance human logistics and crowd control.

"It was crucial to find a launching customer for our building automation applications. This use-case could subsequently be used to prove th technology's benefit and convince other customers of adopting the application." - ***EnOcean***

The same goes for the other companies in this case study. Voltree's customers, the forest administrations, would like to improve wildfire prediction and detection capacity by installing fast sensor networks throughout forests. Autonomously powered, low-maintenance sensing equipment is crucial to make such detection systems economically feasible.

4.2. Increasing scarcity of resources and volatile markets

With regards to powering sensor equipment, there are two competing technologies for energy harvesting: wired technology and battery technology. Increasing prices of the resources needed for these two technologies, e.g. copper or lithium, drive the economical attractiveness of energy harvesting solutions. In comparison, the amount of resources needed for energy harvesters is significantly lower than for wire- or battery powered applications.

In addition, energy harvesting also saves energy consumption compared to wire powered or battery powered applications. Although the energy consumption of for instance a single sensor might be minute, the fast numbers with which these are installed translates into substantial figures. Consequently, rising energy prices increase the added value of energy harvesting solutions.

4.3. The rate of climate change and its impact on society

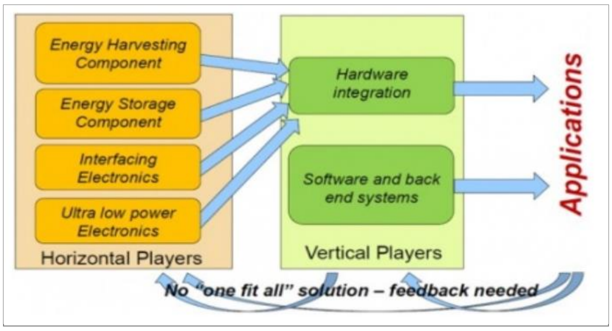
The rate of adoption of energy harvesting technology is driven by the rate of climate change, and its impact on the functionality of every aspect of our current infrastructure.[21] As society is becoming more prone to reduce its environmental impact, the technologies of the companies in this case study help consumers and companies to reduce their environmental impact by reducing energy consumption or to anticipate and mitigate the results of climate change by closely monitoring fragile or high-risk areas and ecosystems.

Whereas energy harvesting technology is currently mainly used to power wireless sensors, technological development might increase their potential as energy generators for our daily energy consumption.

4.4. Standards for interoperability between energy harvesters and application components

As described earlier, an energy harvester almost never functions in isolation. Depending on type of energy source used, the output of electricity can be rather unstable. Therefore one needs additional electronics to maintain a regular electricity supply for system functionalities, as in most application areas, regular measurements are needed for which the sensor requires a stable energy supply. Micropelt therefore had to come up with a power management solution that guaranteed such a stable energy supply. To do so, Micropelt had to analyse the full value chain to decide which components it required and which would be compatible with its system architecture. Standardisation of components would help companies like Micropelt to develop an application around their energy harvesting technology with less analytical effort (Figure 5).

Figure 5: Challenges in the value chain for energy harvesting powered wireless networks



Source: EE Times website on 'Energy harvesting could reach a USD 4.4 billion market in 2021[22]

With regards to standardisation in wireless electronics, particularly the communication protocol is crucial. Depending on the application, standardisation is needed for specific elements or for components of the full system. Standardisation of the energy harvesting solution itself is hard.

For this purpose EnOcean formed an alliance of partners active in component markets for wireless sensors, power management, microcontrollers, RF transmitters and receivers (the EnOcean alliance). Together they developed a wireless standard for building automation devices, which is currently driving demand in the sector.

Setting this certified standard for interoperability between various components in an energy harvesting powered wireless sensing system was one of the biggest success factors for EnOcean. Standardised products have the largest chance of market success, as they provide customers with the opportunity to switch between various vendors. Standardisation increases interoperability of various elements in a wireless building automation network, which included energy harvesters, wireless sensors, power management, microcontrollers, RF transmitters and receivers, and actuators.

EnOcean deliberately did not pursue to develop a proprietary standard, in order to increase adoption rates and enable all partners and vendors to use the standard. Ultimately, this creates most value for its end-customers. A key challenge in energy harvesting is to decide how to use the minute energy level generated in an application. To develop a system approach in which the energy harvester and surrounding equipment can be combined with almost any type of sensor or measurement device opens-up all sorts of application markets.

In addition, standardisation helps to push prices per component down. For Micropelt's application, it was crucial that all required components became available at reasonable prices and volumes. From a technical perspective this was the most challenging aspect.

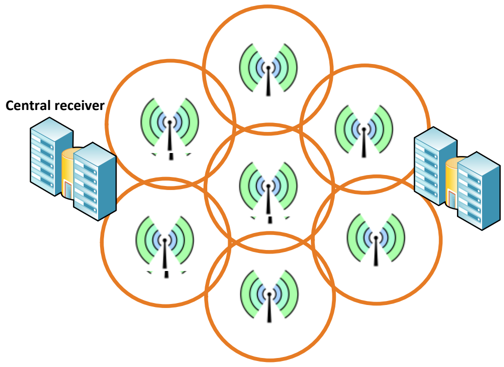
Proprietary standards, on the other hand, can form an obstacle to rapid adoption of energy harvesting solutions. There are numerous examples of companies pushing proprietary wireless standards, which users are unwilling to commit to. In addition, many companies only sell hardware instead of integrated solutions, which should include the software and communication protocol.

4.5. Energy harvesting technology is not yet technically feasible for all applications domains

As energy harvesting solutions generate relatively low-power currents, the sensors and RF components they power also are ultra-low voltage versions. When applied in a wireless MESH network, the transmitter and receiver have to be in close proximity of each other (Figure 6: PwC visualisation of a wireless MESH network). This becomes a problem when setting up a wireless MESH network in a remote and/or extreme location. As there is no central receiver where all collected data can be transmitted to directly (distances are simply to large), these systems are often set up as mesh wireless networks, in which each node in the system not only transmits its own data but also forwards signals of other nodes.

The illustration shows that not all nodes are within direct proximity of the central receivers. Most nodes therefore relay data for the whole network. This creates fragility in the system in case some nodes malfunction or operate in an environment which disturbs the signal.

Figure 6: PwC visualisation of a wireless MESH network



Source: PwC visualisation

The example of Voltree illustrates the above described problem. Energy harvester powered sensors and transmitters do not have the power and reach to form a stable mesh wireless network in a forest environment. Elements like foliage disturbing the low-power RF signals too much to maintain connection between all nodes. As a result, measurements become inaccurate. This is particularly harmful for applications in high-impact contexts like forest fire prediction. This is why Voltree has moved away from mesh wireless applications. Energy harvesting technology is not (yet) suitable for powering mesh wireless networks in remote or extreme locations.

"Energy harvesting technology is not yet suitable for powering mesh wireless networks in remote or extreme locations." - ***Voltree***

5. Policy recommendations

Policymakers can play a vital role in the market adoption of energy harvesting solutions for wireless networks. By establishing minimum safety and quality standards for application of energy harvesting solutions and acting as a launching customer, governments can generate strong signalling effects towards consumers and companies. Simultaneously, heavier taxation of non-renewable energy resources makes energy harvesting more interesting from a commercial perspective.

5.1. Increased taxing of non-renewable energy sources

The environmental benefits of energy harvesting powered application are evident. By powering products with ambient energy which would otherwise go to waste, substantial energy savings can be realised.

In addition, the main substitutes for energy harvesting, wired or battery powered applications are associated with larger, negative environmental impacts. Wire powered and disposable-battery powered systems require more resources to be installed and maintained. Moreover, as EnOcean's Marketing Director stated, "we all know that most batteries of consumers end up in the regular waste cycle and are not properly recycled". The cost price of batteries therefore does not reflect the societal and environmental costs.

Taking these arguments in consideration, there should be some regulation on how batteries are used and recycled in projects. Regulation that correctly allocates total costs of a technology to the price of that technology would make energy harvesting solutions more attractive to customers. Policy support in the form of increased taxes on battery and wire-powered systems, or tax breaks for energy harvesting powered applications, could stimulate adoption of the technology.

5.2. Facilitate standardisation processes for energy harvesting and storage coherence

The importance of standards for interoperability between energy harvesters and application components has already been highlighted. In addition, it was mentioned that several standards for energy harvesting solutions in wireless network application have already been developed.

Policy makers could further support the development, diffusion and adoption of these standards. They could facilitate public standardisation procedures for accuracy of data measurement, coupled to programs and regulations which set minimum safety and quality requirements for energy harvesting solutions in wireless networks. This could create strong signalling effect towards potential users of the technology. It also prevents companies with proprietary standards and patents to frustrate collaboration across the value chain.

In addition, governments could mandate or recommend the use of energy harvesting solutions (and associated minimum safety and quality standards) as they have done with smart meters, RFID, photovoltaic etc. For example, new legislation in the UK requires carbon monoxide sensors in every classroom. In the US, policy makers are considering to implement a law which prescribes automatic tire pressure monitoring.[23] Such applications can easily be outfitted with energy harvesting technology.

Standard labels (guidelines) for energy efficiency in for instance buildings or consumer products can drive the demand for automation systems and energy-efficient equipment. Policy makers could enforce the use of such energy efficiency standards, again with a strong signalling effect to consumers, which helps to spread energy harvesting technology.

The need for standards in energy harvesting from a policy perspective is confirmed by Voltree's CEO Stella Karavas, who states that "nobody wants to be kept hostage by small companies with their patents. Creating public standards for data collection and analytics is crucial, from a government perspective".

5.3. Support in realising pilot projects and acting as a launching customer

As many industries in which energy harvesting technologies might be applied are rather conservative towards new technologies, many energy harvesting vendors are experiencing difficulties in finding launching customers. These are needed to build a track record and to establish proof that the technology is working in a real-life environment.

Governments are operating a large share of public infrastructure. However, companies like EnOcean experience that diffusing innovation to government buildings is very hard. There is no basis for introducing innovation, because government officials are often very conservative. Governments could initiate programs and regulations which set minimum requirements for adopting innovative solutions in their procurement.

Governments could also act as launching customers. They could prescribe the adoption of energy harvesting technologies in public procurement activities. Wireless networks powered by energy harvesters could be installed in public infrastructure.

Investments by policy makers in pilot projects at high—profile locations (e.g. busy traffic junctions or airports) are another method to increase exposure and proof of principle for energy harvesting technology.[24]

This reasoning is confirmed by an example from Pavegen. Currently, there is a lot of infrastructural development in London, in which Pavegen technology might be incorporated. The company is pushing for a pilot installation in a public space, in order to demonstrate to the general public what its technology is actually doing. It would be most beneficial if the London municipality could help to establish a permanent installation at a high profile location.

5.4. Increase public awareness and industrial use through education

One of the issues for the diffusion of energy harvesting is that if you ask someone from the general public whether he has ever heard about thermal or energy harvesting, most people will answer that they are unfamiliar with the technology or its benefits. Companies like Micropelt do not have the marketing budgets to establish this societal awareness. This is where governments could help.

The concept and applicability of energy harvesting solutions could be incorporated in educational curricula, in order to promote the adoption of the technology. The term is also not yet widely adopted in engineering studies, which could stimulate adoption of energy harvesting technology sensors throughout industrial applications.

"Nobody wants to be kept hostage by small companies with their patents. Creating standards for data collection and analytics is key from a government perspective". – ***Voltree***

6. Appendix

6.1. Contacts

Company	Interviewee	Position
Pavegen	Sanaa Siddiqui	PR and communications officer
EnOcean	Andreas Schneider	Chief Marketing Officer and co-founder
Micropelt	Fritz Volkert	CEO and founder
Voltree	Stella J. Karavas	CEO and founder
NikkoIA	Alain Jutant	President and CEO

6.2. Websites

Pavegen	http://www.pavegen.com/
EnOcean	http://www.enocean.com/en/home/
Micropelt	http://micropelt.com/
Voltree	http://voltreepower.com/
NikkoIA	http://www.nikkoia.com/en/

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